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THESIS

AN EXPLORATORY ANALYSIS OF VILLAGE SEARCH OPERATIONS

by

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June 2004

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Following the cold war a new kind of threat emerged; terrorism became the most important threat used by individuals, organizations and countries to reach their goals. Turkey has suffered from terrorism for years. In Turkey, the main logistic resource for the terrorist is the villages located in remote areas. A search operation is one of the techniques used to capture the terrorists. Five village search operations scenarios are developed based on a previous study done for the New Zealand Army and the author's personal experiences. For this study, the agent-based model MANA (Map Aware Non-uniform Automata) is used. To investigate the effects of 16 variables state-of-the-art Near Orthogonal Latin Hypercube Designs are used. With a personal computer and the computational capabilities of supercomputers run by Mitre for the Marine Corps Warfighting Lab (MCWL) approximately 15000 runs are completed. In comparing the five scenarios, the significant effects on the outcome of a possible skirmish in search operations are the proficiency level of the soldiers, the employment of village guards and the support of the local people to the terrorists. The results of the analysis suggest that the most important factor affecting the Blue casualties is the initial speed and synchronization of the Blue search unit entering the village and the most important factor affecting the Red casualties is the Red Stealth.

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AN EXPLORATORY ANALYSIS OF VILLAGE SEARCH OPERATIONS

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ABSTRACT

Following the cold war a new kind of threat emerged; terrorism became the most important threat used by individuals, organizations and countries to reach their goals. Turkey has suffered from terrorism for years. In Turkey, the main logistic resource for the terrorist is the villages located in remote areas. A search operation is one of the techniques used to capture the terrorists. Five village search operations scenarios are developed based on a previous study done for the New Zealand Army and the author's personal experiences. For this study, the agent-based model MANA (Map Aware Non-uniform Automata) is used. To investigate the effects of 16 variables state-of-the-art Near Orthogonal Latin Hypercube Designs are used. With a personal computer and the computational capabilities of supercomputers run by Mitre for the Marine Corps Warfighting Lab (MCWL) approximately 15000 runs are completed. In comparing the five scenarios, the significant effects on the outcome of a possible skirmish in search operations are the proficiency level of the soldiers, the employment of village guards and the support of the local people to the terrorists. The results of the analysis suggest that the most important factor affecting the Blue casualties is the initial speed and synchronization of the Blue search unit entering the village and the most important factor affecting the Red casualties is the Red Stealth.

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

Agent	Most primitive entity in MANA
BATT6	The Sixth Battalion
CO	Commander
DTA	Defense Technology Agency, New Zealand
GUI	Graphical User Interface
ISAAC	Irreducible Semi-Autonomous Adaptive Combat
JMP	Jump, a Statistical Software Package
KADEK	The Kurdistan Democratic Congress
Lt Col	Lieutenant Colonel
MANA	Map Aware Non-Uniform Automata
MATLAB	A Software Package for Doing Numerical Computations
MCWL	Marine Corps Warfighting Lab
MOE	Measure of Effectiveness
NPS	Naval Postgraduate School
NVG	Night Vision Goggles
OR	Operations Research
PKK	Kurdistan Workers Party
PRGN	Pseudo Random Number Generator
SA Map	Situational Awareness Map
SSKP	Single Shot Kill Probability
TRADOC	The Training and Doctrine Command
TRAC	TRADOC Analysis Center
τ	Detectable departure from the mean

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EXECUTIVE SUMMARY

Although there are no commonly accepted definitions of terror and terrorism, the *American College Heritage* dictionary defines terror as "violence committed or threatened to intimidate or coerce, as for military or political purposes," and terrorism as "the unlawful use or threatened use of force or violence to intimidate or coerce societies or governments, often for ideological or political reasons."

Like many of the countries in the world Turkey has been suffering for years from the threat that emerged after the Cold War called terrorism. Today, terrorism is the most prominent threat used by individuals, organizations and countries to achieve their goals, plans or actions. Turkey has suffered from terrorism since the early sixties, which coincides with a time when youth movements were growing around the world. Following the youth movements, the 1980s were the beginning of a new threat facing the Turkish population. This threat is the terrorist organization called KADEK (Kurdistan Democratic Congress), previously known as the Kurdistan Workers Party (PKK). Four students at the University of Ankara, Abdullah Ocalan, Kesire Yildirim Ocalan, Hakki Karaer and Cemil Bayik founded the PKK in 1974. KADEK is based on Marxist-Leninist ideology and aims to establish an independent Kurdish state in southeastern Turkey. KADEK is recognized as a terrorist organization by the United States. [Ref 1] KADEK has been the most lethal terrorist organization in Turkish history.

In order to achieve their goals, terrorist organizations aim to gain the support of the local people while continuing fighting with the security forces. They usually exploit the existing political, economic and social conditions and offer an alternative plan based on their ideology to solve the problems. Any means is considered to be legal to the terrorist organizations to obtain the support of the people. They may try to convince, encourage, force or threaten when necessary. Unlike the terrorist organizations, the security forces that are countering them have to react within the boundaries of the rules

set by law. Public support is the key factor to both sides. While the security forces are countering the terrorist organizations the government takes the necessary measures to ameliorate the conditions causing dissatisfaction amongst the people.

The focus of the security forces in fighting terrorism is on the support links. The security forces aim to cut the support links between the population and the terrorists. For these purposes the security forces conduct different types of operations. Search operations are one of the types of operation conducted in this process and their goals are listed as: [Ref 23]

- To capture the terrorists or to eliminate them.
- To obtain intelligence.
- To isolate the terrorists
- The cut the support link between the population and the terrorists.

In this study we focus on village search operations. Village search operations are conducted with the same goals mentioned above. In Turkey, villages located in remote areas have been the main logistic support for the terrorists. People living in these areas have been convinced, forced or threatened to support KADEK. Throughout this study we focus on the factors that might affect the results of a search operation. The questions in this thesis are based on a previous study done by New Zealand's Defense Technology Agency for the New Zealand Army and the author's personal experience. The study aims to answers the following questions:

- How does the proficiency level of the soldiers attending a search operation affect the outcome of the operation when a skirmish occurs?
- How does the employment of village guards (villagers volunteer to protect their villages against terrorists) affect the results of a village search operations?
- Does the behavior of the villagers affect the search operations? What happens when they are sympathetic to the terrorists?
- Does the employment of a reserve unit provide the necessary assistance to the force conducting a search operation?

In order to answer these questions and to explore the main factors affecting the outcome of a search operation we use the agent-based model MANA (Map Aware Non-uniform Automata). Why do we use an agent-based model instead of a conventional

equation-based model? This is because of the non-linear nature of the low-intensity conflict and the importance of the human component in guerilla warfare. What we mean by the human component can be better explained by an example. Consider a peacekeeping operation. The capability of an equation-based model to explain the non-linearity and intangibles in these kinds of operations is lacking. This is because the human component is the most dominant factor in peacekeeping operations. Let's suppose that the security forces are trying to separate two opponent groups. The factors that might be taken into consideration are the initial aggressiveness of the groups, the fear, and the behavior of the leaders in the groups as well as the techniques and the amount of forces used by the security forces to alleviate the tension of the groups. It is obvious that the model used to simulate such operations should be able to handle non-linearity quite well. Agent-based models provide this ability with agents acting autonomously. An agent is the basic entity defined in an agent-based model. He can sense, learn and act autonomously during the simulation. In this study, we model a scenario in order to investigate the importance of the villagers' behavior in a search operation. MANA provides the ability to model such situations. Propaganda can also be modeled or one can investigate the importance of the behavior of a leader in affecting the groups' behaviors. The factors stated so far are all parts of the intangibles of the human characteristics that can be stated as: fear, leadership, aggression, fatigue, morale, trust, help and so forth.

Another important property of agent-based models is in the ease of modeling. It might take months to model a scenario in one of the conventional models while this process just takes a few days to do it with agent-based models.

To explore the main factors affecting the result of a search operation and to answer the questions stated above, approximately 15,000 runs are made using personal computers and the computational capabilities of supercomputers run by Mitre for the Marine Corps Warfighting Lab (MCWL). Hypothesis tests, bootstrapping and regression trees are the main techniques used in this analysis. Different software packages like JMP (JUMP), S-PLUS and Excel are used throughout the study. The primary conclusions drawn from the analyses are:

- The proficiency level of the soldiers and the equipment used significantly affect the outcome of a search operation. Thus, professional soldiers are preferred to conscripts.
- The employment of village guards is highly beneficial in decreasing Blue casualties, at least as modeled in the scenario.
- The support of the local people is critical to the Blue forces. For a village search operation, the support of the villagers to the terrorists highly affects the number of Blue casualties. The support of the local people is critical to the terrorists too. In particular, they provide caches for them to hide if surprised by the Blue. Figure 1 displays how significant the support is to the terrorists. The number of Red casualties decreases significantly when villagers are sympathetic to the terrorists.

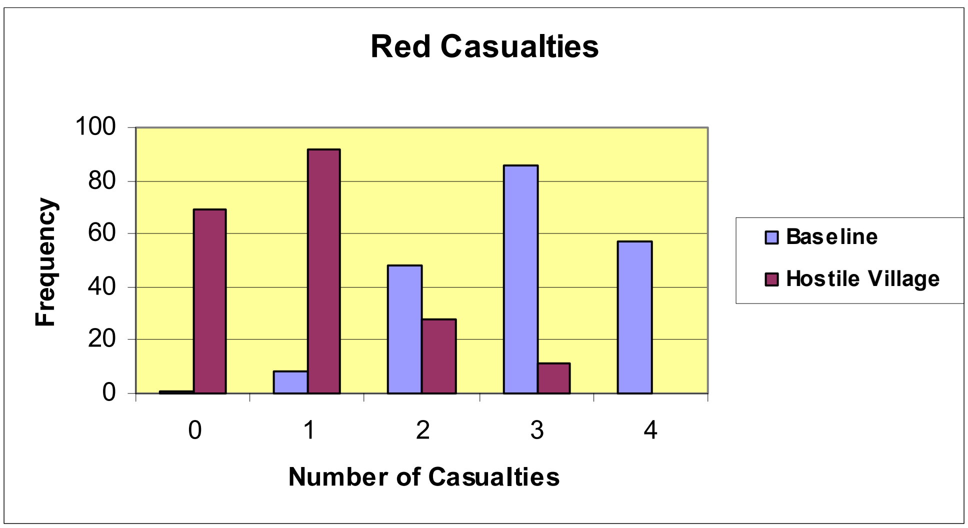
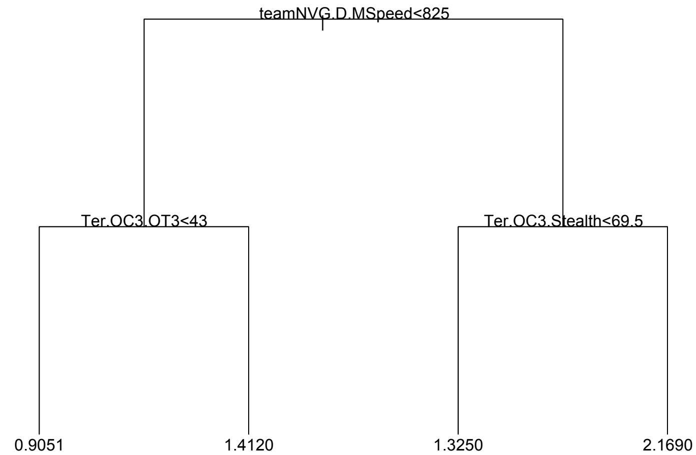


Figure 1. Comparisons of Red Casualties for Both Scenarios

- Intelligence is a key factor for search operations. The Blue forces should have the information about the presence of any kinds of caches or tunnels built in the area.
- The employment of a reserve unit clearly increases the number of Red casualties but may not decrease the number of Blue casualties. In this case, the risk that the commander would like to take should be taken into consideration.
- The speed of the Blue forces inserted into the village is the most important factor affecting the Blue casualties. In Figure 2 the important factors obtained from the regression trees and the linear regression are displayed. Both techniques display the same factors as being the most important factors affecting Blue casualties.



Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
SearchT_MSpeed	1	1	4.934841677	75.49629	5.13E-11
Ter_OC3_Stealth	1	1	4.060424099	62.11891	6.98E-10
Ter_OC3_OT3	1	1	3.032083611	46.38671	2.42E-08

Figure 2. Regression Tree for Blue Casualties and the Most Important Factors Obtained From the Linear Regression of Blue Casualties

- The Red stealth is the most important factor affecting Red casualties and it is also an important factor affecting Blue casualties.
- Red aggressiveness is an important factor affecting both Red and Blue casualties. The casualties of the Blue forces decrease when Red avoids contacting the Blue.
- Reliable communication has an important impact on Blue casualties.
- The presence of civilians impacts the effectiveness of the search operations. This fact reduces the Red casualties by affecting Blue's firepower.

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I. INTRODUCTION

A. CHAPTER OVERVIEW

This chapter provides an explanation of the purposes and the motivation for this thesis. The purpose of the thesis is to answer four operational questions about village search operations using the agent-based model MANA (Map Aware Non-uniform Automata). In this chapter, we also explain the reason for doing search operations in villages, why villages are suitable for terrorist organizations like KADEK (The Kurdistan Democratic Congress), and the nature of this insurgency. We also define the four operational questions for the research and the reasons we use MANA to answer these questions.

B. TERROR AND TERRORISM

There are no commonly accepted definitions of terror and terrorism. Almost all countries and organizations have different perceptions of a terrorist act. A person defined as a terrorist by one country or organization is sometimes defined as a warrior of freedom by others. This makes the war against terrorism more difficult.

While definitions vary, *the American College Heritage* dictionary defines terror as "violence committed or threatened to intimidate or coerce, as for military or political purposes," and terrorism as "the unlawful use or threatened use of force or violence to intimidate or coerce societies or governments, often for ideological or political reasons."

C. THE HISTORY OF TERRORISM IN TURKEY

Following the Cold War, a new kind of threat emerged. Today, terrorism is the most prominent threat used by individuals, organizations or countries expecting to achieve their goals. Turkey has been suffering from terrorism since the early sixties as a result of the youth movements, which arose all around the world. Until the 1980's the Turkish security forces had to deal with these movements. In 1974, students at the University of Ankara, Abdullah Ocalan, Kesire Yildirim Ocalan, Hakki Karaer and Cemil Bayik founded Turkey's most lethal terrorist organization: KADEK, known previously as PKK (The Kurdistan Workers Party). The US government also recognizes KADEK as a terrorist organization. [Ref 1] Based on Marxist-Leninist ideology KADEK aims to establish an Independent Kurdish state in southeastern Turkey. Since 1984, KADEK has

killed 5,546 security guards, 4,027 of these guards were soldiers, 1,265 were village guards and 254 were policeman. In addition, a total of 11,383 security guards were wounded. Furthermore, in these incidents, a total of 4,561 citizens have been killed and 5,860 wounded. [Ref 1]

D. THE NATURE OF INSURGENCY

To succeed, insurgencies mobilize material and human resources as support to achieve their goals, actions and plans. With mobilization, the insurgencies obtain the necessary human resources and supplies. The reason these terrorists can secure a large-scale mobilization and financial support is owing to the dissatisfaction of the population with the current social and political conditions. The insurgent leadership offers a new program that exploits the dissatisfaction of the local people. The insurgent leadership then uses all means to transform the public's dissatisfaction into political action. [Ref 3]

> The primary goal of the insurgents is to receive the active support of a plurality of politically active people and the passive acquiescence of the passive majority. [Ref 3]

Winning the support of the population is the key factor of victory for the insurgent group. The same objective applies for counter-insurgency. Both sides attempt to convince the population about the justice of their policies. In order to reach its goal, the insurgent group will use any means necessary, such as threats, force or propaganda. But the counter-insurgency is expected to adopt only positive measures. KADEK also use the same means; it encourages, forces or threatens people to raise money or to assist its members' needs and in this sense the villages assume a crucial role. The main sources of support for KADEK activities come from internal and external donations and from drug trafficking. Since KADEK mostly operates in rural areas, one of its weaknesses is its dependency on local support, which allows the security forces to control KADEK's movements and intervene.

Intelligence is a crucial issue. All counter-insurgency operations should be based on intelligence. Thus, an effective tactical intelligence network is highly important to the security forces. In order to maximize the information, security forces should closely coordinate with the local population.

E. RESEARCH QUESTIONS

The villages in southeastern Turkey are a primary source of members, money and logistics for the insurgent group. Thus, countering KADEK requires controlling the villages. The Turkish Armed Forces have conducted successful search operations in villages since 1984, which has been of critical importance in defeating KADEK. In August 2000, I was assigned as a company commander in Turkey's Special Operation Forces. During this duty, I participated in some village search operations that were based on intelligence reports.

The purpose of this thesis is to investigate the various outcomes of one of those operations in a designated village, if a skirmish had occurred. Special areas to explore include:

- Different units in the area conduct search operations. Some consist of conscripts and some consist of professional soldiers. How does the proficiency level of soldiers conducting a search operation affect the hypothetical Blue (security forces), Red (insurgent group), and neutral (villagers) casualties?
- The Turkish government employs village guards who voluntarily protect their village against terrorists. The guards, who are provided some small arms and radios, are one of the main sources of intelligence. How do village guards affect a search operation?
- The support of the local people is crucial to the insurgency and counter-insurgency. How does this support affect a search operation?
- A model has been built for the New Zealand army by New Zealand's Defense Technology Agency (DTA) and applied to a village search operation. Their conclusions are that the speed at which an inner cordon is inserted is critical to the success of a cordon and search mission; also blocking tactics are superior to chasing tactics. [Ref 4] In this model, no reserve units are deployed. But, usually in search operations commanders maintain a reserve unit for flexibility purposes. How would a reserve unit affect the possible outcomes of a village search operation?

This research employs an agent-based model MANA (Map Aware Non-uniform Automata). [Ref 6]

F. WHY AGENT-BASED MODELS (MANA)?

All models are wrong, but some are useful.

- George E. P. Box

> Guerrilla warfare is military and paramilitary operations conducted in enemy-held or hostile territory by irregular, predominantly indigenous forces. [Ref 3]

By nature, guerilla warfare differs from conventional battles and can be considered as a peoples' war. The goal is to win the support of the local population while fighting the enemy. Thus, the local population sometimes becomes either the object or the subject of the struggle. [Ref 5]

The highly non-linear nature of guerilla warfare makes it impossible to model with equation-based models. The main disadvantage of equation-based models is that they cannot analyze the dynamic, emergent behavior of guerilla warfare.

> Furthermore, the non-linear nature of equations describing many real-world phenomena makes equation-based models extremely sensitive to initial conditions. [Ref 6]

This means that small changes in determining initial conditions can produce totally different outcomes. This is a serious challenge to conventional models.

In the following section, the useful features and the relative advantages of agent-based models are discussed.

> An agent is an object or an entity that can act with its own set of rules. An agent-based simulation is a model that consists of those agents. [Ref 7]

As mentioned earlier, conventional models fail to explain all of the real-world phenomena. The ability to consider emotional behavior is probably the principal advantage of agent-based simulations. Even though no quantitative data exist to represent these intangibles (aggressiveness, fear, courage, leadership, cohesion, discipline or morale) agent-based models give the analyst the opportunity to explore different alternatives.

Everything should be made as simple as possible, but not simpler.

- Albert Einstein

While one considers the necessary details of combat, military plans should be simple enough to be understood and applied by the practitioners of combat. The same rules apply to the world of simulation. Models should contain the essence of the situation and disregard the unnecessary details to avoid overwhelming the computer or the user. In this sense agent-based models are good tools to use; they are fairly simple and easy to set up. While it takes months to build a scenario in traditional constructive models, just days or weeks are needed for the same process with agent-based models. Furthermore, a simple model leads to fast runs. Hundreds of thousands of runs can be done in twenty-four hours with an agent-based model. This attribute provides the analyst or the modeler the opportunity to run the simulation with many different alternatives. This is in contrast to conventional large-scale models, which usually enable the analyst to consider only a few alternatives due to slow runs and complex modeling.

Entities in traditional constructive models are often pre-programmed, and they act perfectly. But systems in the real world may not ever work or act properly; they can diverge from their usual attitude. In real-world combat, sometimes soldiers, due to a host of reasons, may not obey their orders or may accidentally kill their own comrades in a conflict. Accidental fratricide is a reality recognized by military doctrine, and it is an example indicating that systems do not always act perfectly. Such an idea can be modeled with agent-based models, as the autonomous characteristic of agents allows one to model entities that can make mistakes, or make wrong decisions or can accidentally kill their comrades.

The emergent behavior of real-world situations can be modeled with agent-based models. Agents interact with their local environment, with the enemy, and with the friendly troops. Owing to their situational awareness capability, agents can sense and adapt to their local environment and act accordingly.

Although agent-based models are useful tools to explore small-scale situations, they have some limitations. For instance, they can’t be used for prediction or used to model large-scale real-world situations. Another major challenge for agent-based models is the difficulty of representing intangibles as numerical data.

1. Why MANA?

MANA builds on and complements the earlier ISAAC/EINSTEIN Cellular Automata (CA) models developed by the Center for Naval Analyses, and the now discontinued Archimedes models that were designed for the Marine Corps. MANA's primary use is a "distillation" tool. That is, it creates a bottom-up abstraction of a scenario that captures just the essence of a situation, but avoids the unessential detail. MANA was designed to explore key concepts that ISAAC (at that time) was unable to explore. In particular: [Ref 6]

- **Situational Awareness:** A group memory of enemy contacts. Two types of situational awareness maps are provided in MANA: a squad map which holds direct squad contact memory and an inorganic map that stores contact memories provided by other squads through communications links. [Ref 6]
- **Communications:** Allows communication of contact sightings between squads. An extensive range of parameters allows issues involving communications links to be thoroughly explored. [Ref 6]
- **Terrain Map:** Contains terrain features such as roads that agents can follow and undergrowth that agents can use for concealment.
- **Waypoints:** Can define a set of waypoints, not just an ultimate destination. [Ref 6]
- **Event-driven personality changes:** Events such as being shot at; taking a shot, reaching a waypoint, making enemy contact can all trigger a different personality set, which lasts for a certain time. Personality changes can be for individuals or for a whole squad at once. [Ref 6]

II. CHARACTERISTICS OF URBAN WARFARE

This chapter details the characteristics of urban warfare and the similarities between villages and urban areas. Due to its unique conditions, combat in urban areas can result in massive casualties for both the attacker and defenders. In order to reduce collateral damage, firepower might be restricted in populated areas. Another factor restricting urban operations is the presence of civilians in the area. The necessity to provide life support and other essential services to civilians can require the allocation of a large number of manpower and equipment for this purpose. A hostile population can strongly affect the mission accomplishment by different means (passing information, providing shelter to the enemy, and so on). Success in such an area might be defined as accomplishing the mission while minimizing possible civilian casualties and environmental damage. Initially, the defender has a tactical advantage over the attacker, as he knows the terrain. However, in the following phases of the battle, the advantage of mobility, cover, and observation can be shared evenly. Also, surprise can go to attacker in search operations. This section discusses some of the unique characteristics of urban warfare. [Ref 8]

The battlefield for urban operations consists of a mix of natural and man-made features, which distinguish it from all other kinds of terrain (e.g., forest, jungles, or deserts). The commander can encounter open and covered areas in the urban terrain and areas where these coexist. The battlefield in an urban area merits a detailed analysis because of its effect on the tactics and procedures employed by the unit. The use of armored vehicles in such an environment requires close coordination with infantry units. While increasing the cover and concealment capability, the urban areas decrease firepower and the lines of sight. The defender can use the features that restrict firepower and visibility to create an area that the attacker desires to avoid.

In addition to fighting on the ground level, urban combat operations may also be conducted on roofs, from buildings, sewer systems, in subways, and other underground facilities. Providing increased concealment and cover for the defenders, this feature may

result in severe casualties and material destruction for the attackers in the initial phases of the battle. When visibility is diminished, the need for automatic weapons, hand grenades, and high explosives increases.

An effective communication network is crucial either for the defender or the attacker to achieve a successful operation. However, in urban areas, the communication network can be seriously affected.

> In possibly no other form of combat are the pressures of battle more intense. Continuous close combat, high casualties, the fleeting nature of targets, and fires from a frequently unseen enemy produce severe psychological strain and physical fatigue—particularly among small-unit leaders and soldiers. [Ref 8]

The complexity of the terrain and the existence of civilians tend to reduce the effectiveness of standard military tactics. These operations require a different tactical use of military units. Generally, small units with decentralized command and control networks are the essence of combat operations in an urban area.

Except for the presence of high buildings, villages are very similar to the urban area in respect to military operations. The presence of civilians, the cover and concealment factor, the necessity to use small units, the composition of the terrain that mixes natural and man-made features, fewer observational areas, and the need to use light infantry arms are all also characteristics of village search operations. Therefore, in terms of basic military tactics, operations conducted in villages are similar to those conducted in urban areas.

A. SEARCH OPERATIONS IN BUILT UP AREAS

Search operations in populated areas are either conducted by military forces or by police forces. The operations might comprise just a few cottages or a densely populated area. For both areas, special units must be employed. Methods for search operations are represented in the field manual as: [Ref 9]

- Search units consist of three elements: (1) The search element responsible for conducting the search. (2) The security element that encloses the area to prevent any entrance or exit and to secure the area for the search unit. (3) The reserve unit (a mobile unit maintained in a nearby area) that is usually kept for flexibility purposes and employed when required.

    - The search element itself is divided into different components and while conducting the search it has a special team for its close security.
    - The security element encircles the area to prevent any reinforcements from entering or exiting. After the security elements surround the area, the search element enters the region to conduct the search. All potential exits that could be used by the evaders must be cut-off by the security element. Those potential areas could be subsurface routes, such as subways and sewers for urban areas, and tracks/caches or tunnels for villages.
    - Upon the decision of the commander, the reserve element can be assigned to reinforce or to replace any of the other two elements if they meet resistance that they cannot overcome.
- A component of the environment that should be taken into consideration is the population. In counter-guerrilla operations, the support of the population is extremely important to the security forces. So, the search operation should be conducted in a way that causes limited disturbance to the population. The amount of disturbance should encourage the local population to pressure the guerrillas to retreat from the area, but the disturbance should not encourage the population to help the guerillas. For success, the search plan must be executed swiftly and simply.

B. EXAMPLES OF RECENT SEARCH OPERATIONS

This section gives recent examples of search operations and an insight about the benefit of using the agent-based model MANA in search operations. The first example is the capture of the former Iraqi leader Saddam Hussein, who was captured during a search operation conducted by the coalition forces. The New Zealand Army in East Timor conducted the second search operation. Before this operation, the New Zealand's DTA conducted a study involving different tactics that could be used.

1. Capture of Saddam Hussein

The capture of Saddam Hussein is one of the recent search operations conducted by the coalition forces in Iraq. The following are press releases from the Headquarters of the United States Central Command. Figure 3 and Figure 4 display the area where Saddam Hussein was found.

> Forces from the 4th Infantry Division, coalition forces and special operations forces captured former Iraqi dictator, Saddam Hussein, at approximately 8 p.m. local time on the fourteenth of December 2003 in a remote farm house near Tikrit, Iraq. Operation 'Red Dawn' was launched after gaining actionable intelligence identifying two likely locations near

the town of Ad Dwar. The First Brigade Combat team of the 4th ID was assigned the mission to capture or kill Saddam Hussein. The forces involved in the operation consisted of approximately 600 soldiers including cavalry, artillery, aviation, engineer and special operations forces. The forces cleared the two objectives, but initially did not locate their target. An additional suspicious site was identified and searched. The area was a small, walled, mud hut compound with a metal lean-to structure. Within the structure a ‘spider hole’ entrance, camouflaged with bricks and dirt was located. The hole was about 6 to 8 feet deep with space allowing an individual to lie down. Saddam Hussein was found hiding at the bottom of the hole. He was captured without resistance and is in the control of coalition forces at an undisclosed location. Items confiscated during the raid include two AK-47 rifles, a pistol, $750,000.00 U.S. dollars and one taxi. Two other individuals who have not been identified were also detained. [Ref 10]

A similar situation is modeled in this study. Terrorists hidden in a cache will likely try to protect themselves and this fact presents a danger to a search operation. This is similar to a Turkish operation against the terrorist organization, KADEK, which has been responsible for numerous casualties.

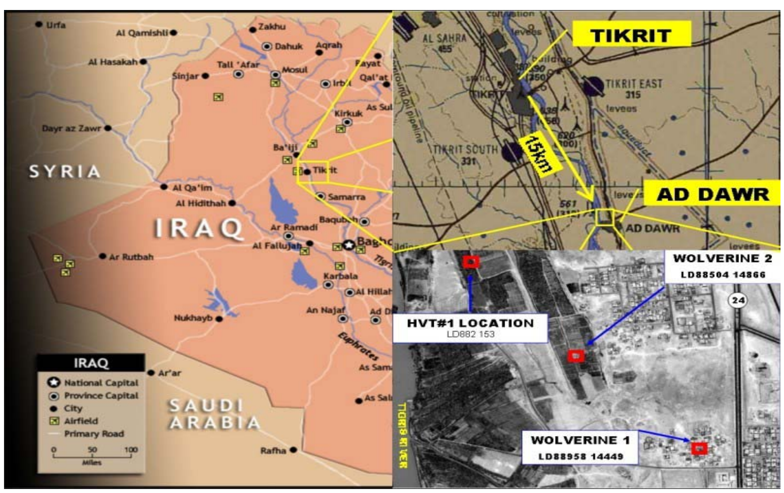

Figure 3. The Area of the Search Operation for Saddam Hussein

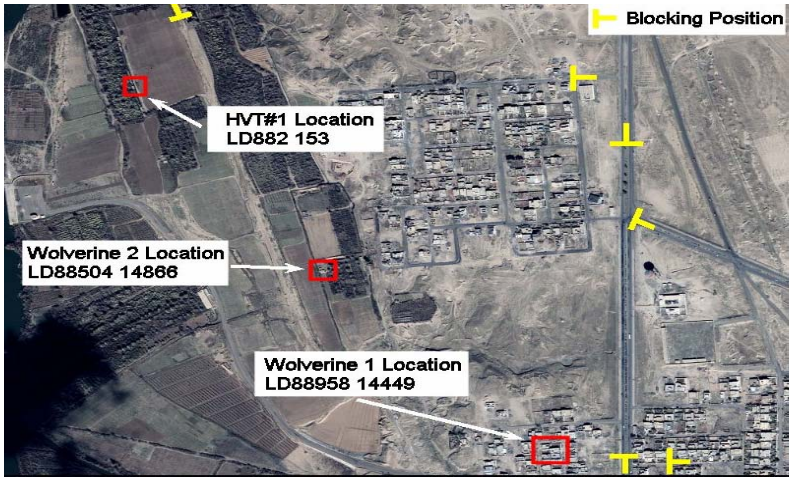

Figure 4. The Area of the Search Operation for Saddam Hussein

2. An Application of the MANA Model to Operations in East Timor

A motivation for this thesis is a study done for the New Zealand Army, using the model MANA, of a village search operation. This section provides an example of a real-world situation implemented previously in MANA. The model was based on two operational questions: (1) What is the most effective way to conduct a search operation? (2) Is it possible to show the benefits of the use of tracks? [Ref 4] Those questions were asked by the BATT6 CO, Lt. Col Dean Baigent, who was concerned that the use of conventional search techniques would not be appropriate for the East Timor theatre.

Conventional search techniques (described in the previous section) suggest the use of an inner and outer cordon. But, Lt Col Dean Baigent was concerned that the time and commotion required for human traffic and dogs to infiltrate an inner cordon would alert the target. Thus, the target could escape from the inner cordon. Once the inner cordon is avoided, it is extremely difficult to capture the target, as the area between the inner and outer cordon is very large. Additionally, the size of the area makes it impossible to implement a full outer cordon, due to a lack of resources. Lt. Col Dean Baigent identified MANA as a useful tool in exploring the possible different techniques for the search operation. Finally, the models were built for different scenarios and the conclusions were: [Ref 4]

- The speed at which an inner cordon is inserted is critical to the success of the cordon and search mission.
- Blocking tactics were superior to chasing tactics for catching belligerent infiltrators.

The BATT6 conducted two cordon operations following the completion of the models. Although there was a long time between the modeling and the search operations, and although the models were not intended to explore all of the aspects of the operations, comments from the CO and other staff revealed that the exercise of setting the scenarios in MANA was highly beneficial, and the study amplified their confidence in the methods that were actually used.

III. SCENARIOS AND MODEL DESCRIPTION

A. CHAPTER OVERVIEW

This chapter describes the modeling of the scenarios built for this thesis, focuses on key features of the agent-based model MANA (Map Aware Non-Uniform Automata), and explains the measures of effectiveness and the sixteen factors defined for the analysis of the baseline scenario. Five different scenarios are built in order to answer the four operational questions mentioned previously. Company size commando units are employed in all five scenarios.

B. SCENARIOS

The first two scenarios intend to explore the following factor: the effect of the proficiency level of the troops on the outcome of a possible skirmish in a search operation. The third scenario examines the benefits of having village guards in a search operation. The objective of the fourth scenario is to explain the effects of a hostile environment on the outcome of a search operation. The fifth scenario is modeled to find how effective a reserve unit is in a village search operation.

1. Baseline Scenario

To search the village and capture the terrorists, an outer cordon is placed around the village and then an inner cordon is inserted. The third step is to send the search element in the village. Unlike a conventional search operation, in this scenario the outer cordon is placed 1500 meters away from the village. The reason for placing the security element far away from the village is the fear that dogs, which would alert the terrorists, might detect the soldiers. The drawback of placing the troops far from the village is the impossibility of forming a full cordon. The lack of resources forces the commando unit to set up a partial cordon focused on blocking the tracks that are in the areas believed most likely to be used by the terrorists.

In the first two scenarios the villagers are not sympathetic to the terrorist group. This means that the villagers will not pass any information to the Red agents (terrorists). The operation starts at 1 AM and lasts around three hours; just a few local people are awake at that time.

The actions follow this sequence: a company size unit approaches the village by foot using the road and forms an outer cordon. Then, two sniper teams sneak into two observational points approximately three to four hundred meters from the village. Finally, the search team divides into two components and is inserted following the roads from the north and from the south. The terrorists are probably in the village for propaganda, food or money. The terrorists do not want to take any risks, so they will try to evade as soon as they obtain any information of an imminent threat. The dogs, which realize the trucks are coming, will bark and this will be the information about possible danger that is passed to the terrorists.

> MANA allows modeling this via the 'interactions' feature. This feature enables a model entity to trigger a change in the state of another entity within a certain range. In this case, the change in the state indicates that information has been passed. [Ref 4]

A map of the village was adapted for use by DTA (New Zealand's Defense Technology Agency) in the model using color codes. An elevation map is created using Photoshop. Altitudes in MANA can be defined via the different tones of the 256 colors on the grey scale, each tone represents 10 meters. The elevation for each hundred meters is coded in this map. Entities are used to represent dogs (green), villagers (yellow), terrorists (red) and soldiers (blue), see Figure 5.

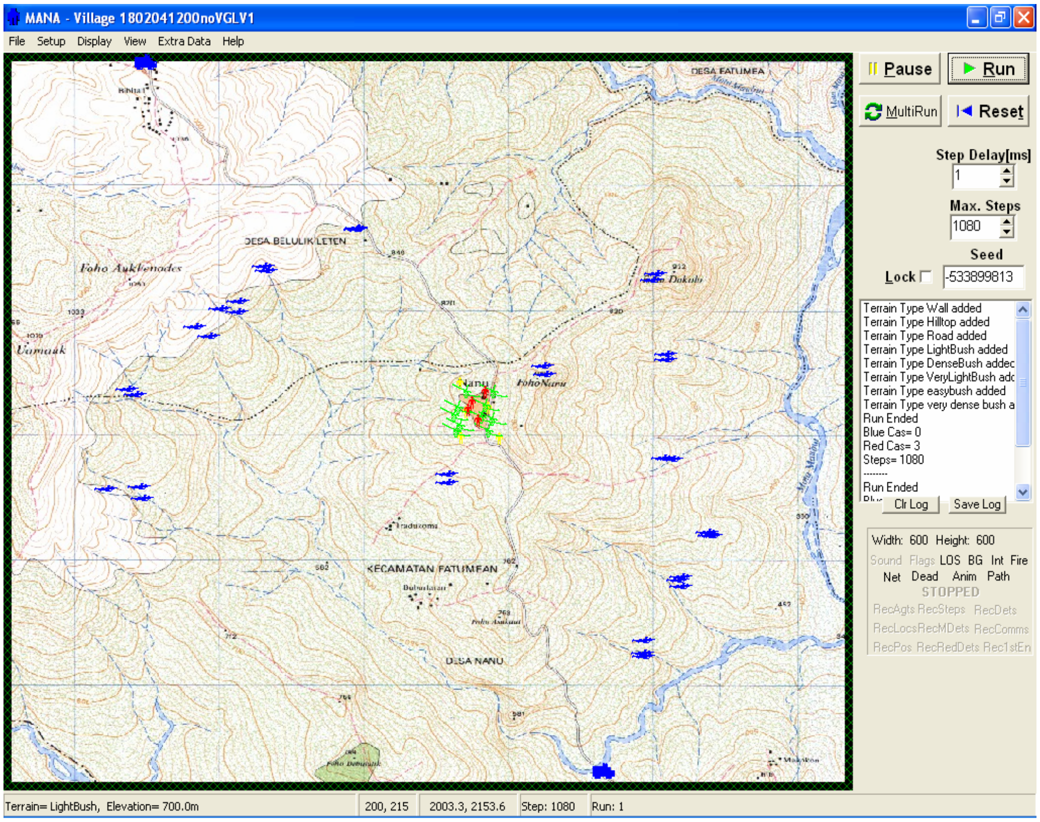

Figure 5. A Snapshot of the Baseline Scenario

2. Key Scenario Assumptions

- The terrorists will run away from the soldiers, and desire to follow tracks and creeks in order to escape. However, they will not surrender—which means that they will fight if they cannot run away.
- Troops on the ground that do not carry NVGs (Night Vision Goggles) have a visibility of 80 meters. The troops carrying NVGs have a visibility of 200 to 600 meters, depending on the capability of the NVGs used. The troops that are positioned on the outer cordon and do not have NVGs have a detection capability of 100 meters. This superiority is given to these troops because of their positions.
- The terrorists are assumed to have NVGs, but they are incapable of hooking them up to their rifles. They have the same firing range as the troops but are considered to be more experienced than conscripts, so they have a higher single-shot kill probability.
- The dogs are aroused as soon as the trucks are within a range of 700 meters of the village.
- The snipers are not detected.
- The troops are able to dismount the trucks as soon as they reach their final waypoint (an area close to the village).

The terrorists are familiar with the area, so they have a higher speed than the conscripts. The speed of the terrorists is 3 kilometers per hour (km/h) and the speed of the conscripts is 2.77 km/h (this is not the case for professionals)

3. Professional Soldiers

A company size professional unit is employed for the mission. The same procedure described in the previous scenario follows.

- Assumptions
    - Professionals have the same speed as the terrorists. That is, they have a speed of 3 km/h.
    - Being better trained, the professional's stealth values are 10 percent higher than the conscript's stealth values. This means that it is more difficult to detect them.
    - Professionals have a higher single-shot kill probability than conscripts; for the range defined, depending on the arms that the soldier uses, a professional's single-shot kill probability is at least 10 percent higher than the conscript's.
    - Professionals have better equipment than conscripts, so they tend to have higher detection ranges and probabilities.4

4. Village Guards

The Turkish government in its fight against terrorism employs village guards. These are people that voluntarily protect their village against terrorists. The guards are provided small arms and some equipment to accomplish their mission. An area of interest in this study is to see how effective the village guards are in a search operation area, if a skirmish occurs.

Village guards are represented with entities of the color purple. They have a high stealth parameter initially, which means that they will not be detected most of the time. Their primary mission is to observe the terrorist activities in the village and pass the information to the security forces. Having been provided NVGs, they have a 150-meter range of visibility. Except for self-protection, village guards will not engage in a fight with the terrorists. When security forces arrive at the village, the guards will join them and attend the rest of the operation with the troops. It is assumed that the dogs are familiar to the guards, and their presence will not be revealed.

5. Hostile Village

This scenario examines the case in which the villagers are sympathetic to the terrorist group. The contribution of the local people to the guerilla forces can be providing food, money, shelter, members and information. Villagers represented with yellow agents in the model pass information about the approach of strangers to the terrorists, in addition to the dogs. As soon as the terrorists receive the information, they seek refuge. In this case the refuge will be a cache. It is assumed that some villagers have underground tunnels and caches in their house. The problems for the security forces in such cases are (1) It is difficult to find the terrorists; (2) The security forces become very vulnerable to close fires. Any skirmish occurring in these conditions might cause severe casualties to the troops. MANA allows modeling such cases by its “interaction” and “terrain” features. The principle for the interaction feature was described previously in this chapter. The terrain in MANA is modeled by color codes. Each color code has three factors scaled from 0.00 to 1.00. The first one is “going.” A value of 0.00 means the terrain is impassable; a terrain of 0.50 means that the terrain is passable but affects the movement of the entity reducing its speed by 50 percent, and a terrain with a value of 1.00 can be crossed without any difficulties. The second factor is “cover.” A cover value of 1.00 means that the area protects entities from being killed, and a value of 0.00, means that no cover is provided at all. For a cover value between zero and one there is a corresponding probability of killing the agent. The third factor is concealment. Concealment affects the visibility. A value of 1.00 for the concealment factor means that it is impossible to detect the entities in this area. For a value of 0.00, the concealment is taken together with the stealth factor of any entity to decide whether it is detected or not. When the concealment takes a value between 0.00 and 1.00, a random test reveals whether a grid square can be seen through on each time step. For any of this parameter there is a percentage reduction if the number is defined between zero and one. For example, a cover of 0.50 means that this area provides 50 percent less cover than an area that has a cover of 1.00. Areas with high cover values are very attractive for an agent seeking refuge. This is the case in this scenario. The Red agents will move toward the

area with high cover value, which represents a cache constructed in some of the houses of the village. It is assumed that terrorists who entered the cache will have a lower visibility and firing range.

6. Reserve Unit

Conventional techniques of a search operation require the use of a reserve unit in search operations to assist either the search element or the security element when needed. This scenario is built to see the effects of maintaining a reserve element when a cordon and search procedure is implemented. The reserve unit is carried by a helicopter, and initially will have an aerial observation task. The reserve forces would be dismounted either when the helicopter detects Red agents or when a friendly unit sends information declaring the presence of Red agents. The reserve team will be dismounted in an area nearby the contact.

- Assumptions:
  - The pilot has a depth perception of 500 feet. The reserve element is provided high capacity NVGs. Thus, any entity within a range of 500 meters will be detected.
  - The troops will dismount the helicopter within thirty seconds.
  - All soldiers are provided NVGs and have a visibility range of 200 meters.

C. HISTORY AND KEY CONCEPTS OF THE MODEL (MANA)

This section intends to provide additional information about the model used in this study and refers to the history and some key features of the model based on [Ref 6].

1. History

In 1999, DTA was using two automaton models, ISAAC and EINSTein [Ref 12], developed by Andy Illachinsky to do some exploratory analysis. The idea of replacing the conventional models with these automaton models created the necessity to improve certain aspects of these models. Then, in early 2000, DTA began to use the program MATLAB to introduce the idea of “Situational Awareness.” But MATLAB did not provide the needed flexibility for this concept. The idea of using an object-oriented program emerged, and Delphi Object Pascal language was chosen to serve this purpose.

In the early stages of its creation MANA and ISAAC had similar concepts, but several new features have been improved in MANA. The following section presents the key features of MANA.

2. Key Concepts

2.1 Squads: A squad is a set of agents that can vary in size from 1 to a 1000. [Ref 6] Once a squad is defined all agents in the squad have the same properties. A transition between states (The properties of the current behaviors defined by a set of parameters) can be done either individually or as groups. In addition to having common properties agents share the same situational awareness map.

2.2 Battlefield Object: A battlefield of 200 by 200 cells is created by default. The size of the map can be extended to 1,000 by 1,000 cells. Each cell can be occupied by a single entity unless modified to allow multiple agents in a cell. No agents can cross the border of the Battlefield boundaries. The following types of cells can be created in MANA:

2.2.1 Billiard Table: This is the basic terrain that has no properties and does not affect the behavior of the entities. These cells cannot be modified.

2.2.2 Easy Going: This is the terrain preferable to the agent's movement. Entities that desire moving easily will prefer these areas. Yellow is the color code for easily passable terrain. Areas around this color must affect the movement of the agents in order to make them undesirable.

2.2.3 Wall: The color grey is used to create walls. A wall is an area that cannot be occupied by agents.

2.2.4 Light/Dense Bush: The color green and its tones represent light or dense areas. The density level of the area affects the movement, cover, and concealment factors of the entities in the model.

2.2.5 Hilltop: Is an area suitable for indirect fire represented by grey coloring.

A standard Windows bitmap is used to set up the area. Additionally, a background can be created for explanatory or decorative purpose. A background reflecting the properties of the battlefield is useful in making the situation more comprehensible.

2.3 Squad SA Map (Situational Awareness Map) Object: When a squad member detects an entity using its sensors, it sends this information to the squad situational awareness map, see Figure 6, which is a platform where entities are in pictorial forms. The other members of the same squad can share this information as they use the same platform as their squad SA map. Choosing the organic situational awareness option in the view menu, one can see the map where the information is collected and shared. Types of icons to represent entities, threat level association and cluster targets are the options on the squad SA map. The arrow on the bottom allows displaying the squad SA map for different squads. In the squad SA map, inverted triangles represent friends, non-inverted triangles are other friendly squads, and diamonds indicate neutrals. Enemies are shown as Red boxes, unknown (entities detected but not classified) as white boxes, and cluster targets as pink circles.

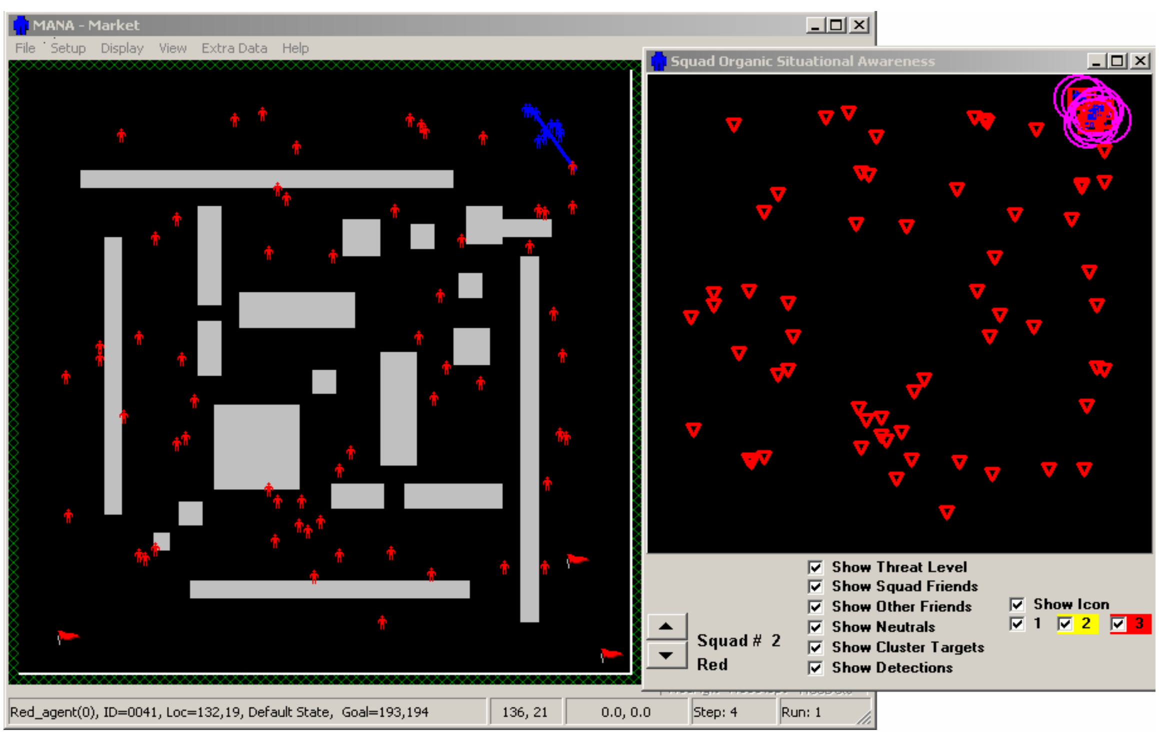

Figure 6. Squad Situational Awareness

Threat persistence is the parameter that defines the time period each entity will be displayed on the SA map. As soon as the time period is exhausted and no new detection has occurred, the icon representing this entity disappears from the squad SA map.

The inorganic situational awareness map shows information about the entities detected by other squads and is similar to the squad SA map, with the exception that on the inorganic situational awareness map, the “Show Squad Option” is removed.

Agent Object: Owing to the situational awareness property of MANA, the agent object can sense its environment, it knows where it is, it can instinctively move toward and away from other entities, and it can pass the information about its location and the location of other objects that it detects to other specified squads. An agent object can perform some state changes if some conditions are met. Weightings can define the traits of the agent object. See [Ref 6] for a detailed discussion on inducing different behaviors by selections of weights.

2.5 Movement: Movement is the most important activity of a MANA agent. The agent checks all grid squares that are within its movement range and selects the one that best fulfills its desire to move toward or away from other entities. The agent also considers its current location; it can also prefer to stay there. The following steps describe the movement algorithm:

2.5.1 The agent considers all of the movement possibilities within its movement range.

2.5.2 It considers the locations where no other entities are present.

2.5.3 Among the possible locations, it selects the one that it is allowed and that most fulfills its desire according to its personality weights.

2.5.4 If some modifiers like cluster constraint, combat constraint, minimum distance are defined, then the agent acts accordingly. If it has several movement choices that are of equal desirability, it randomly selects one.

> 2.5.5 The Penalty Calculation: The penalty calculation finds the move with the least ‘penalty.’ Moves are possible to grid squares within ‘movement speed’ squares of the current location and not already occupied by an agent or impassable terrain. [Ref 6]

If several moves have a similarly low penalty, a move is chosen at random from the good moves. The 'movement precision' parameter sets how wide the margin should be for accepting similarly good moves. Setting the movement precision to a low value will mean that most often only the best move will be chosen and the movement will appear very deterministic. If the movement precision is too great, the agents tend to wander about in a Brownian motion, as moves are selected at random. [Ref 6]

The tendency of agents to move toward or away from other objects is independent of the distance. It does not make any difference to the agents whether the object is 100 meters away or 200 meters away from him, unless the entities are included in the penalty calculation. When this is the case, closer entities are given higher weighting than others. The penalty to move to any grid location is the sum of 27 penalty calculations, corresponding to the 27 personality parameters listed in Table 1 in Appendix A. The equation used to calculate the penalty is

$$\text{Penalty} = 1 + \frac{\sum_{m=1}^{M} (D_N(m) - D_O(m))D_W(m)}{100\sum_{l=1}^{M} D_W(l)},$$

where M is the number of entities whose distance from the agent is to be used in the weighting equation; D_N and D_O are the new and old distances respectively from the agent to each entity; and D_W is a weighting factor that by: [Ref 6]

$$Dw = Round\ (BDL - D_0),$$

where BDL is the length of the diagonal of the Battlefield. *Dw* assigns a higher value to the entities closer to the agents over those that are found farther. The reason for including the diagonal length is to ensure that the scale of different scenarios does not affect the calculation. [Ref 6]

The penalty for moving towards or away from other agents is normalized by the number of agents weighted in proportion to their distance from the agent (it is assumed that all agents occur in close proximity). For example, if an agent is attracted to friendly agents, it seeks to minimize its weighted average distance to friendly agents within its sensor range. However, a number of constraints can modify this attraction. The minimum application and maximum influence distances sets a defined area about the agent in which the penalty calculation is made–entities from outside that area are not included in the penalty calculation. [Ref 6]

2.5.6 Cluster Constraints: Cluster constraint is a feature in MANA that prevents agents with the same allegiance from clustering over a specified number. When an agent intends to move, the friend's penalty component of the movement is calculated. If the number of friendly agents in an area within the sensor range is found to be greater than the cluster constraint, then the friend's penalty is counted and if not it is ignored.

2.5.7 Combat Constraints: The combat constraint prevents the agents with the same squad to move towards the enemy without a certain numerical advantage. The numerical advantage is obtained by subtracting the number of enemies from the number of agents in the same squad. Note that the number of friendly agents in other friendly squads is not considered.

2.5.8 Advance Constraint: The advance constraint prevents one from moving toward the next waypoint (goal) unless the number of friendly agents reaches a specified numbers. The movement can occur only if the number of the agents within the sensor range is over a specified number.

2.6 Random Numbers: The random numbers generated in MANA are obtained using the built-in Delphi function 'Random'. Delphi uses a pseudo random number generator (PRNG) with a cycle of 2^{32}. It maintains a 32 bit seed, which is treated as an unsigned integer. The result can take on approximately 4.3×10^9 values (2^{32}) before repeating the cycle. [Ref 6]

When the MANA application is started, the Delphi function Randomize is called which sets the random number generator with a random seed obtained from the system clock. The Random function is used many times during a MANA model execution. For example: in determining moving and firing order, for stealth calculations, deciding the best of similarly good agent moves, when getting shot (SSKP), and when placing agents at the start of a run. [Ref 6]

In the MANA source code, the Random function is normally called to return an integer number in a certain range. A typical example would be the firepower calculation. In the agent 'get shot' function, a random number between 0 and 100 is calculated. If this number is less than the SSKP (an integer between 0 and 100) of the enemy agent who shot, then the receiving agent is hit. As one would expect, a high SSKP (close to 100) results in receiving agents being shot most of the time. [Ref 6]

D. MEASURES OF EFFECTIVENESS (MOES)

Most of the time, for a commander, a successful mission accomplishment in a village search operation means maximizing the number of Red casualties while minimizing the casualties of his own forces. For this reason, in this study two primary measures of effectiveness are chosen: the mean Blue and the mean Red casualties. Although these measures can represent the goal of a commander in a search operation, they were insufficient for comparing the five scenarios. Therefore, a third measure of effectiveness, the ratio of mean Blue to mean Red casualties (also known as the exchange ratio), is introduced to fulfill this deficiency.

1. Mean Blue Casualties (MOE 1)

The purpose of defining this MOE is to compare the five scenarios from the Blue losses aspect. This also forms the response variable for the data set and is used to explore the significance of the sixteen factors—that is, what factors affect Blue losses.

2. Mean Red Casualties (MOE 2)

This MOE provides a measure to compare the five scenarios from the Red losses aspect. This is also used in the data set to explore the effects of the sixteen factors.

3. The Ratio of Mean Blue Casualties to Mean Red Casualties (MOE 3)

This MOE is introduced for a special case. MOE 1 and MOE 2 provide the necessary information in most of the comparisons, but when we were comparing the baseline scenario and the scenario with the reserve unit, we were unable to favor one of the scenarios with these MOEs. Thus, we decided that the ratio of mean Blue casualties to mean Red casualties would be a good measure of effectiveness to use. This helps us reach a conclusion for the comparison.

E. THE SIXTEEN FACTORS DEFINED FOR THE ANALYSIS

Below are the sixteen factors that we use in the analysis. The original names of the factors are given in parentheses. New names are defined to obtain a better pictorial form with the plots.

1. Ter_OC3_EasTer (Terrain): In the scenarios it is assumed that the terrorists will follow tracks in order to escape from the security forces. In MANA, agents tend to follow easily passable terrains, and the tracks are defined as "easy terrain." The reason for defining this factor is to explore the effect of this assumption on the outcome of the search operation. In other words, what if the terrorists do not prefer to follow these terrains?

2. Ter_OC3_InjFr (Injured Friends): This factor defines the willingness of the terrorists to help their injured friends.

3. Ter_OC3_sskp (Single-Shot Probability of Kill): This factor is defined to find the effects of the single-shot kill probability of the terrorists on the outcome.

4. Ter_OC3_Stealth (Stealth): This parameter is defined to find how the stealth of a terrorist affects the outcome. The stealth parameter in MANA represents the difficulty of detecting an entity by another one when it enters its sensor range. A stealth value of 100 means that the entity is invisible. Conversely, a stealth value of 0 does not affect the visibility of the entity at all. [Ref 6]

5. Ter_OC3_OT3 (Enemy Threat3): This factor defines the propensity of the terrorists to move toward or move away from the security forces. We want to explore the effect of the aggressiveness of the terrorists.

6. Ter_OC3_SR (Sensor Range): This parameter varies the terrorist's ability to classify the enemy and examines its importance.

7. Sniper1Stealth (Stealth): As mentioned previously, two snipers are infiltrated to observational points in the scenarios. It is assumed that the dogs or the villagers do not detect the snipers. What if one of the snipers was not careful enough and was detected? The goal of defining this factor is to look at how the individual mistakes of a sniper affect the outcomes.

8. SearchT_FWP_Stealth (Stealth): One of the most vulnerable moments of a search team in a real-world situation is when they dismount the vehicles after reaching the final destination. This factor is described to find the affect of varying the stealth value of the search team when it reaches the village and dismounts the vehicles.

9. SearchT_OC3_Stealth (Stealth): This factor intends to explore the effect of the stealth parameter for the search team while conducting the search operation. The point is to find how much better the search team would do with higher stealth values or vice versa.

10. SearchT_MSpeed (Movement Speed): Speed is very important in search operations. Research has shown that a high speed is usually preferred for a search operation. Then, how fast should a search team be for a search operation? Is there a relationship between the attitude of the terrorists and the speed preferred?

11. SearchT_OC3_OT3 (Enemy Threat 3): This factor defines the propensity of the security forces (the search team) to move toward the terrorists. Soldiers may obey or not obey their commander in a military operation, or for some reasons the search team may not pursue the terrorists. The questions that arise are what happen if the security forces do not chase the terrorists? Is the cordon tactic enough to capture the terrorists in this case?

12. SearchNoNVG_SR (Sensor Range): This factor varies the sensor range of the search team elements that do not carry night-vision goggles. This factor also intends to explore the effects of having a different sensor range.

13. TC_ComRel (Communication Reliability): Communication is vital to any military operation. In MANA, a perfect communication network can be defined. But this will not reflect reality. It is assumed that the elements (the search element and the cordon) in the scenarios have perfect inner communications. Defining this factor, we wanted to examine the role of communication in a search operation.

14. SearchT_ITR (Inorganic Threat Rate): The inorganic threat rate is the number of time steps that must pass for a threat on the Inorganic Situational Awareness map to disappear. [Ref 6]

An example can explain better: Let's say that a terrorist is detected by one of the cordon's elements and this information is passed to the search team. This information will appear on the situational awareness map of the search team element. This information will stay on the situational awareness map until the deadline. If the inorganic threat is 30 (the time defined), then the entity will disappear from the inorganic situational awareness map in 30 time steps.

15. SearchT_sskp (single-shot kill probability): This factor is defined to find the effect of the single-shot kill probability of the search team on the outcome of the operation.

16. SearchT_NT (Non-target Classes): Due to the presence of civilians in the area, urban operations are different from most other military operations. Civilians should not be targeted, and this idea somewhat affects the firepower of the forces in the area. In the scenarios, the search operations are conducted during the night. So there are just a few villagers awake at that time. The objective for defining this factor is to find if the presence of so many villagers really affects the outcomes.

This chapter described the five scenarios modeled for this thesis, detailed the key features of the agent-based model MANA, the MOEs and the sixteen factors defined for the analysis of the baseline scenario. The next chapter explains the statistical tools and techniques we use to explore the models.

IV. ANALYSIS METHODOLOGY

A. CHAPTER OVERVIEW

This chapter explains the analysis methodology and the statistical tools used to explore the research questions. The objective of the analysis is to compare the five different scenarios described previously and to explore the effect of the sixteen factors stated in the previous chapter on the possible outcomes of the village search operation scenario in MANA (Map Aware Non-uniform Automata). We also want to develop descriptive and predictive models for the data sets obtained from the MANA application of the village search operation. For these purposes, two different statistical techniques, Hypothesis Tests and Regression Trees, are used.

B. HYPOTHESIS TESTING

> A statistical hypotheses or hypothesis is a claim about the value of a single population characteristic or about the value of several population characteristics. In any hypothesis testing, there are two contradictory hypotheses under consideration. One of these hypotheses is initially favored. This initially favored claim will not be rejected in favor of the alternative unless sample evidence contradicts it and provides strong support for the alternative assertion. [Ref 15]

In this study, the null hypothesis is the claim that the differences of mean Blue and mean Red casualties between the baseline scenario and each of the other scenarios is zero. The alternative assertion is that the difference specified above is not zero, it is either greater or less than zero.

The hypothesis testing procedure that we use requires the assumptions of normal distribution and known values of standard deviations for both samples, when sample sizes are small. However, when sample sizes are large, the Central Limit Theorem (CLT) ensures that the difference between the population means has approximately a normal distribution. [Ref 15] In our case, we do not need to make any assumptions. Because, in order to compare the scenarios, 200 replications are made for each scenario and each result produced by a replication represents a sample from the population. This means

that the sample size is 200 for each population. This number is well above the common CLT thumb rule, which states that the means of sample sizes over 30 are usually close to normally distributed.

C. THE BOOTSTRAP, A RESAMPLING TECHNIQUE

From the researchers' point of view in statistical analysis, a single point estimate is usually insufficient for an estimate of a parameter. For a statistical analysis, usually, the standard deviation, the mean and a confidence interval of the true value of a parameter are of interest. [Ref 16]

Most of the techniques used by a researcher to find the standard deviation and a confidence interval are based on the CLT and the approximation to the normal distribution. These techniques can be invalid when the distribution of the statistic, or its known transformation, is not asymptotically normally distributed. With the computational power gained today, researchers do not need to make such assumptions to estimate the distribution of a statistic. They can use resampling techniques, such as the Bootstrap, that can generate estimates of the standard error and confidence intervals on most statistics developed by the researchers. The statistic representing the third MOE in this study is an example of a statistic that the Bootstrap can provide inferential results when the traditional parametric methods fail. [Ref 16]

In the Bootstrap, the observations that are in hand are assumed to represent the underlying population. Based on this assumption, each time, a number of samples equivalent to the sample size are drawn with replacement from the observed data, generating a distribution for the statistic. In other words, each time the observations are drawn with replacement from an observed data set assumed to be the population itself. In the Bootstrap some of the data points appear zero times, some of them appear just once, and some appear more than once in each draw. [Ref 17] This process is replicated "B" times (a number specified by the researchers, usually suggested as a thousand). The statistic is calculated for each of the B Bootstrap samples. The spread indicates the variability inherent to the statistic, in our case the exchange ratio. (See S-PLUS 4 Guide to Statistic [Ref 17] for more detailed information).

D. POWER CALCULATION AND SAMPLE SIZE

The Power calculations determine the necessary sample size for a hypothesis test with the sensitivity level desired by the analyst. Two types of errors can occur in hypothesis testing. A Type I error occurs when the null hypothesis H_o is rejected, despite being true. A Type II error occurs when H_o is false but it is not rejected. [Ref 15] The Type I error is controlled just by defining a significance level (α). The probability that a Type II error occurs is β, and 1-β defines the power of a test. The power of a hypothesis test is the probability of favoring the alternative when it is true by correctly rejecting the null hypothesis. For a fixed α, and a fixed alternative, to increase the power (or to decrease the probability of a Type II error) the sample size must be increased. This is because; the power of a test is related to $\sum \mu_i^2 / \sigma^2$, where μ_i is the set of unknown means and σ^2 is the variance of the response. [Ref 18] Power calculations are done to determine the sample size that reduces the Type II error to the level desired by the analyst. For this study, the S-PLUS code developed by Lloyd Brown [Ref 18] is implemented and the result shown in Figure 7 is obtained. The y-axis is the number of samples and the x-axis is the detectable departure.

> The detectable departure is called τ. τ is the degree of sensitivity that the analyst wants to incorporate in the hypothesis test, and $\tau = \sum \mu_i^2 / \sigma^2$. [Ref 18]

The figure shows that a sample size of fifty is large enough for a power of 0.95 to catch departures of size .25 (For further details see Brown's thesis).

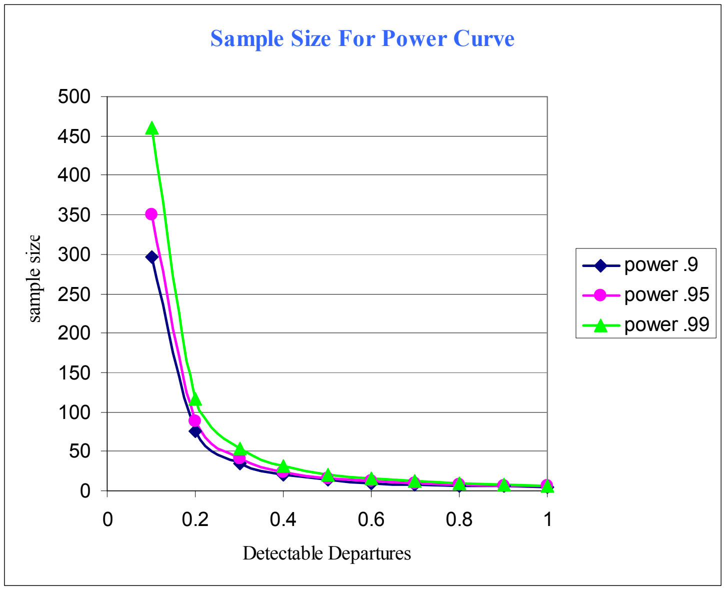

Figure 7. Power Curves Determining the Needed Sample Size

The sample size obtained from these power curves helps us to determine the number of replications needed for our analysis.

E. DESIGN OF EXPERIMENT AND LATIN HYPERCUBE DESIGNS

An experimental design is usually necessary when there are several factors to explore simultaneously in an analysis. The following characteristics are the desired aspects of an experimental design generating results that can be explored efficiently: [Ref 19]

- Approximate orthogonality of the input variables. The orthogonality guarantees independence among the columns (variables) of a design matrix.
- Good space-filling properties. Good space filling properties are favored because they ensure that the design points are distributed throughout the entire experimental region. This also mitigates the model obtained from the analysis being overly influenced by unrealistic influential points.
- Ability to examine the effects of several factors.
- Simplicity in generating the design. The simplicity of generating the design can be explained better by an example. Suppose that a design has sixteen factors and all of their interaction terms should be tested; though only a few are expected to be significant. In a full factorial design 2^{16} (65,536) runs must be done. Even with a half factorial design 2^{15} (32,768) runs must be done. Only 65 runs are needed with near orthogonal Latin Hypercube designs.

The ease of generating the design, the good space-filling property and the near orthogonality provided by the Latin Hypercube designs encouraged us to use them as the experiment tool. Furthermore, we decided to use Lieutenant Colonel (LTC) Tom Cioppa's near orthogonal Latin Hypercube designs. [Ref 19]

> In Latin hypercube sampling, the input variables are treated as random variables with known distribution functions. For each k input variables, labeled X_i, for $i=1,2,\ldots,k$ 'all portions of [X_i's] distribution are represented by input values' by dividing its range into 'n strata of equal marginal probability $1/n$, and sampling once from each strata.'[Ref 20] For each X_i, the n sampled input values are assigned at random to the n cases –with all $n!$ possible permutations being equally likely. This determines the column in the design matrix for X_i and is done independently for each of the k input variables. A great strength of the Latin hypercube designs is that they are easy to generate for all k and n. [Ref 14]

Sixteen variables are defined for the exploratory analysis conducted in this thesis. For these factors sixty-five design points are generated with Latin hypercube designs and for each design point fifty replications are done. In total, 3,250 replications are done.

F. REGRESSION TREES

Regression Trees provide an exploratory tool to discover the organizational aspect of a data set. Tree-based model can be useful in assessing the accuracy of liner regression models (linear regression models predict a continuous response, as a linear function of predictors) and providing predictions rules and information about a large data set [Ref 16]. They can also be used as an alternative to linear regression models. The following are attractive properties of the tree-base regression models: [Ref 21]

- They are easy to understand.
- They are invariant to monotonic transformation in the response.
- They provide a satisfactory treatment of missing values.
- It is easy to obtain and visualize general interaction forms.
- They can handle different type of variables simultaneously.
- They can be used as a predictive tool.

The basic principle of tree models is to partition the data set into binary homogenous nodes. The algorithm recursively splits the nodes, either until the nodes

reach a certain purity measure or until only a few observations remain in each node. In S-PLUS the purity measure is defined as $\left(\sum\left(y_i - \text{ybar}\right)^2\right)$, where y is the response variable for i=1,2,3,…n and ybar is the mean of the response variables.

For example, let's say that we want to predict the wages of people according to their age, education, sex, race, etc. Let *y* be the wage, which is the response. Initially, we have a cell that contains all of the y's. The purity which is usually the deviance $\left(\sum\left(y_i - \text{ybar}\right)^2\right)$ of this cell is measured. The observations may be divided according to sex. Men may receive a higher wage than women, or vice versa. At this stage, the purity is measured again for this specific cell. Another split can occur for education. Men with a certain level of education may receive a higher wage. The process follows the same steps until a certain purity measure is reached or the number of observations in a node is sufficiently small. (See [Ref 21])

G. STATISTICAL TOOLS USED IN THIS STUDY

1. S-PLUS

S-PLUS is a statistical software package used for data analysis. S-PLUS provides a large range of modeling techniques, the ability to view, organize, and edit data, and the ease of specifying a model to explore the data and do an the analysis. The attractive properties of S-PLUS are: [Ref 16]

- Import and edit data sets obtained from many sources.
- Visualization techniques including three-dimensional graphics reveal the complex relationships in a data set.
- The ease provided by the graphical user interface (GUI) allows using complex modeling techniques without writing any code.
- The ability to define functions.

We found S-PLUS useful for this study as a visualization and a modeling tool. In this study, S-PLUS is used for hypothesis tests, regression tree models and Bootstrapping.

2. JMP (JUMP)

JMP is the name of a statistical software package that is very easy to use. JMP provides a point-and-click method of analysis. The analyst does not need to learn the

details of JMP scripting language. He can learn how to use JMP in three or four hours and benefit from the various statistical abilities provided by JMP. With the ease provided by JMP, the researcher can focus on the analysis rather than the tool. Some of the attractive characteristics of JMP are: [Ref 22]

- JMP provides interactive graphical techniques that allow the analyst to explore and uncover the structure of the data.
- Makes it easy to understand the characteristics of the data set by its visualization tools.
- Allows grouping, editing and viewing data sets.
- Helps the researcher find patterns in the data set.
- Fits models according to the types of the variables.

JMP is designed for both a beginning statistician to do simple statistical analysis and for an advanced researcher to perform complex statistical analysis.

This chapter described the analysis tools and the methods used to do the analysis. Finally, the 16 factors are defined. The next chapter explains the results obtained from these techniques.

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V. RESULTS

A. CHAPTER OVERVIEW

This chapter explains the results obtained from the analysis of the data set as well as the results obtained from the comparisons of the five scenarios. Simple test procedures are followed to find whether each of the scenarios is significantly different from the baseline scenario. Classification trees are the primary tool used to analyze the data set. S-PLUS and JMP are the statistical packages used to provide statistical estimates of the effects of the variables and the differences in the five scenarios.

B. COMPARISON OF THE SCENARIO WITH HYPOTHESIS TESTS

In order to do comparison tests, one should define the null hypothesis, the alternative hypothesis and the significance level (α) that controls the type I error. An estimate of the variances should be known or estimated. In the following sections we used Large Sample Tests. When sample sizes are large enough (as a rule of thumb 30 or more) no assumptions on the normality of the populations and known variance are needed. The *Z*-test allows making the comparison in this case. [Ref 15] The following definitions are used in all of the comparisons.

- X_1 is the mean Blue casualties for the baseline scenario and Y_1 is the mean Blue casualties for the scenario involved in the comparison.
- X_2 is the mean Red casualties for the baseline scenario and Y_2 is the mean Red casualties for the scenario involved in the comparison.
- The null hypothesis $H_o:\ X_i - Y_i = 0.$
- An alternative hypothesis is defined for each scenario.
- The level of significance is $\alpha = 0.05.$
- m_1 and m_2 are the sample sizes.

1. Test for the Difference between the Baseline Scenario and the Professionals

This test compares the first two scenarios. In the first scenario, conscripts conduct the search operation. In the second scenario, professionals conduct the operation as they are modeled in MANA (Map Aware Non-uniform Automata). In the real-world environment, professionals are expected to be better trained than conscripts. In the scenario called professionals, in order to model professional soldiers we modified

conscripts. We increased their movement speed, their stealth value and their single-shot kill probability by 10 percent. Due to the difference of equipment, a proportion of the professional soldiers also have a higher sensor range. Since the professionals are modeled with these properties, we expect that the outcome of a search operation conducted by professional will result in lower Blue casualties and higher Red casualties.

a. Difference between Blue Casualties for Both Scenarios

The bar charts in Figure 8 displays the number of Blue casualties for the searches conducted by conscripts (baseline scenario) and by professionals. The y-axis represents the frequency of Blue casualties for the 200 replications made. The x-axis represents the number of casualties. The bar chart suggests that there is a difference between the scenarios in terms of Blue casualties. It should be noted that around 120 operations conducted by professionals results in zero casualties, while this number is 80 for the conscripts. According to the chart, most of the time operations conducted by professionals results in favorable results for the Blue Forces. A hypothesis test is done to prove the difference analytically.

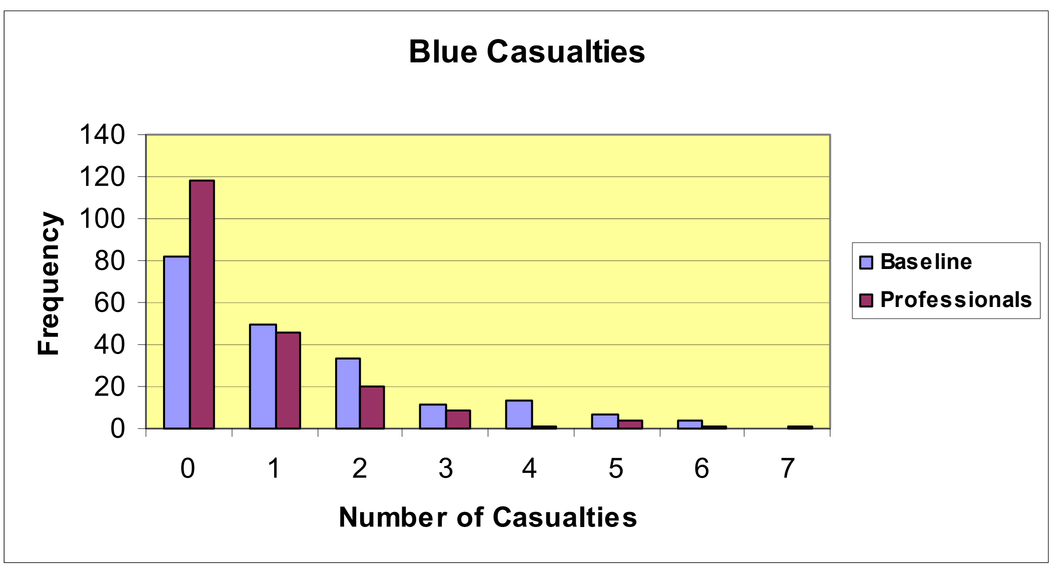

Figure 8. Comparison of Blue Casualties for Both Scenarios

As explained previously, professionals are assumed to be better trained and more experienced than conscripts. The result of a search operation conducted by professionals would be expected to result in lower Blue casualties than a search

conducted by conscripts. In the hypothesis test, the null hypothesis suggests that there is no difference between the two scenarios. In other words, it states that there is no difference between a search conducted by professionals and a search conducted by conscripts. Contrarily, the alternative hypothesis suggests that there is a significant difference between the scenarios, and that the difference between the mean Blue casualties of these scenarios is greater than zero:

- $H_a : X_1 - Y_1 > 0$
- $\overline{X} = 1.3 \quad \overline{Y} = 0.75$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 2.36 \quad s^2_y = 1.485$
- P-value << 0.00001

As the *P*-value is close to zero, we strongly reject the null hypothesis and decide that a search conducted with professionals would result in lower average Blue casualties—at least as we modeled them. It should also be noted that the conscripts suffer on average two times more casualties than the professionals. We can say that there is a significant difference between the two scenarios. In other words, the proficiency level of the soldiers is an important factor in decreasing the number of Blue casualties.

b. Difference between Red Casualties for Both Scenarios

The chart in Figure 9 shows the number of Red casualties for the searches conducted by conscripts and by professionals. The y-axis represents the frequency of Red casualties for the 200 replications made. The x-axis represents the number of casualties. The chart suggests that there is a significant difference between both scenarios in terms of Red casualties. The Professionals are able to eliminate all of the four terrorists in around 150 replications and this number was around 60 for the conscripts.

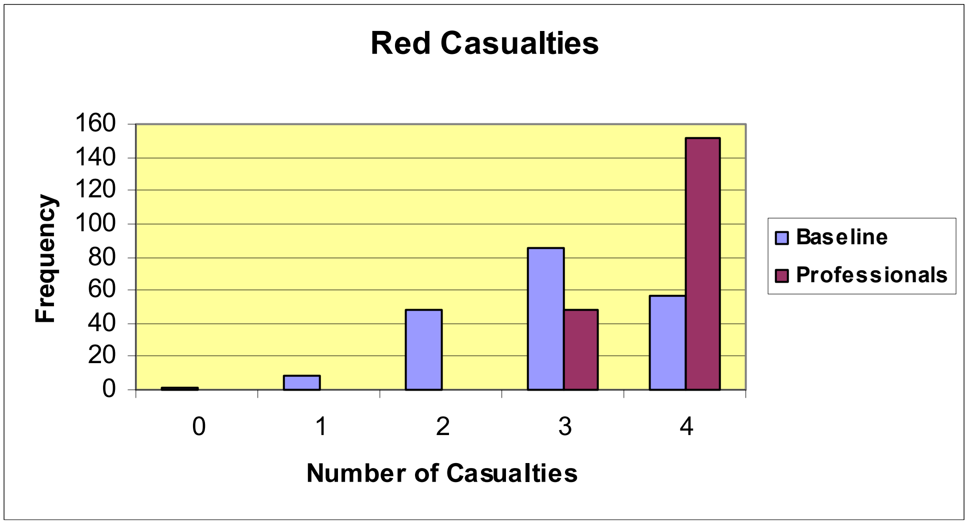

Figure 9. Comparisons of Red Casualties for Both Scenarios

As professionals are assumed to be better trained and more experienced than conscripts, a search operation conducted by professionals should result in a higher number of Red casualties than a search operation conducted by conscripts. Remember, we are assuming that the terrorists will fight or flee, not surrender. Again, the null hypothesis suggests that there is no difference between both scenarios, or assumes that there is no difference between a search conducted by professionals and a search conducted by conscripts. Contrarily, the alternative hypothesis suggests that there is a significant difference between the scenarios, and the difference between the mean Red casualties of these scenarios is less than zero:

- $H_a : X_2 - Y_2 < 0$
- $\overline{X} = 2.95 \quad \overline{Y} = 3.76$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 0.73 \quad s^2_y = 0.18$
- P-value << 0.00001

The *P*-value indicates that the data strongly support the alternative hypothesis. The null hypothesis is rejected.

Remember that in both scenarios we defined four terrorists. $4 - \overline{X}$ ($\overline{X}$ is the mean number of Red casualties for conscripts) is the mean number of terrorists that escape the search operations conducted by the conscripts and $4 - \overline{Y}$ ($\overline{Y}$ is the mean

number of Red casualties for professionals) is the mean number of the terrorists that escape from search operations conducted by the professionals. Notice that the average number of terrorists that escape from search operations conducted by conscripts is four times higher than the number of terrorists that get away from search operations conducted by professionals. We conclude that the proficiency level of the soldiers affects the outcome of search operations in terms of Red casualties.

In both tests, the null hypothesis is rejected in favor of the alternative hypothesis—which claims that the proficiency levels of the soldiers affect the outcomes of search operations in terms of Red and Blue casualties. One can say that obviously when soldiers have better equipment and are better trained; any operation conducted by these soldiers should have better results. In fact, we want to emphasize the importance of this combination. We want to show how much better a professional unit can perform. The conclusion might be that instead of having a large number of soldiers, it may be preferable to have a small number of better-trained and better-equipped units.

2. Test for Difference between Baseline Scenario and Village Guards

Village guards are employed in villages to protect their village against terrorists and to provide the necessary intelligence to the security forces. In the scenario the village guards are located in an area close to the terrorists. In the real-world environment this can be a house where the village guards can observe terrorists' activities. The village guards have a visibility of 150 meters, and they are provided radios to send the necessary information to the security forces. The village guards will not engage in a fight with the terrorists until the security forces arrive in the village. As soon as the search unit enters the village the village guards will join the search unit and pursue the terrorists. One might expect that when village guards are employed, the result of the search operation would decrease the Blue casualties and increase the Red casualties. When observing the scenario, we see that when the village guards pass the information to the Blue forces, the Blue forces are alerted and move accordingly. The Blue forces know where the terrorists are (at least the initial location) and focus on the area of detection. This helps to decrease the number of Blue casualties. Below is the analytical explanation of the comparison.

a. Difference between Blue Casualties for Both Scenarios

As can be seen in Figure 10, the bar charts comparison indicates a significant difference between the two scenarios in terms of Blue casualties. The y-axis represents the frequency of Blue casualties for the 200 replications made. The x-axis represents the number of casualties. In 150 replications of the Village Guard scenario the number of Blue casualties is zero while this number is around 80 for the Baseline scenario. For most of the time, the search operations conducted by conscripts (when there is no village guard) end up with higher Blue casualties.

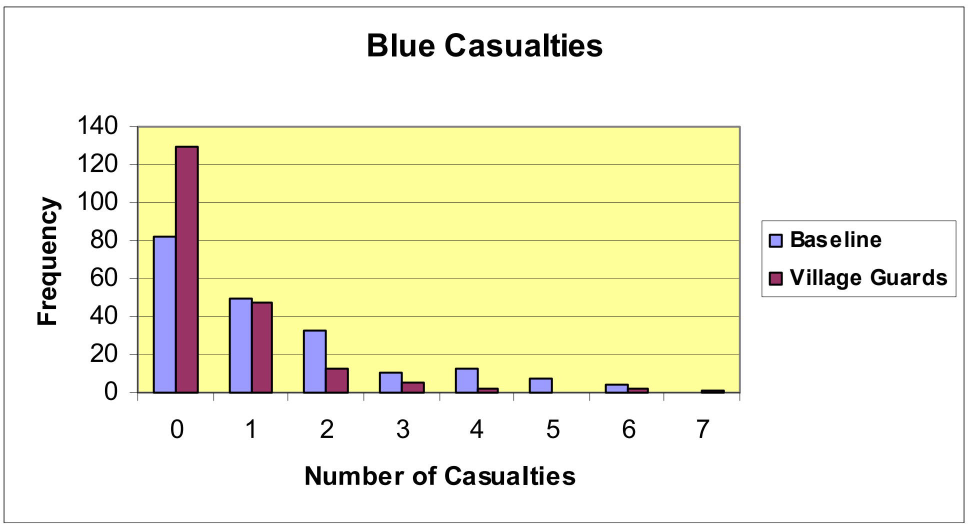

Figure 10. Comparisons of Blue Casualties for Both Scenarios

The alternative hypothesis suggests that the employment of village guards would be helpful to the security forces and this will decrease the number of the Blue casualties. Then the difference between the mean Blue casualties is greater than zero.

- $H_a : X_1 - Y_1 > 0$
- $\overline{X} = 1.3 \quad \overline{Y} = 0.575$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 2.36 \quad s^2_y = 1.16$
- P-value << 0.00001

Notice that the mean number or Blue casualties decreases by 226% when village guards are employed. The *P-value* shown above strongly suggests that there is a

significant difference between both scenarios. In other words, as we modeled them, the employment of the village guards provides a valuable help to the security forces in decreasing the number of Blue casualties. The decrease in Blue casualties is because the village guards send the information about the location of the terrorists until they lose their track.

b. Difference between Red Casualties for Both Scenarios

Examining Figure 11, we cannot say that there is a significant difference between both scenarios in terms of Red casualties. A hypothesis test is conducted in order to find whether there is a difference between both scenarios in terms of mean Red casualties.

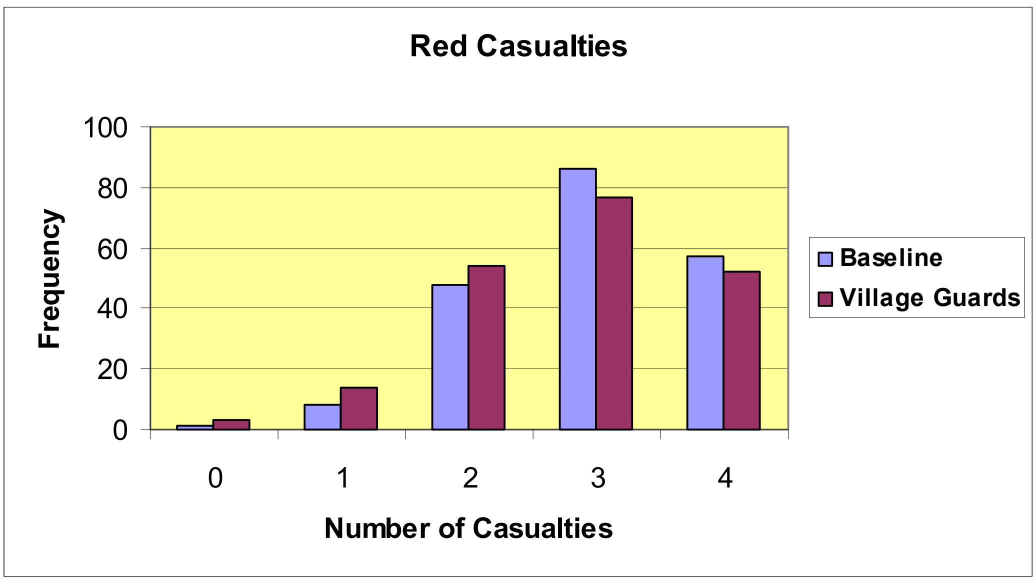

Figure 11. Comparisons of Red Casualties for Both Scenarios

The alternative hypothesis suggests that the employment of the village guards would increase the number of Red casualties. Then the difference between both scenarios would be less than zero.

- $H_a: X_2 - Y_2 > 0$
- $\overline{X} = 2.95 \quad \overline{Y} = 2.81$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 0.73 \qquad s^2_y = 0.91$
- P-value = 0.0537

In this case we retain the alternative hypothesis, but just barely. However, the difference is not significant. This means that the employment of the village guards do not contribute significantly to increase the number of Red casualties. This is reasonable for this specific scenario, as the village guards mostly do an observational task instead of engaging terrorists. Although the employment of the village guards decreases the Blue casualties, it does not increase the Red casualties. In the baseline scenario, the search unit does not know where the terrorists are. While searching the environment, some of the soldiers run into the terrorists—who have higher line of sight or single-shot kill probability. This fact increases the number of Blue casualties. But, when village guards are employed, the Blue forces know for a certain time where the terrorists are, and instead of running into them inadvertently they are ready to fight. Finally, the overall evaluation of both scenarios shows that the employment of the village guards would be favored, as this decreases the number of Blue casualties.

3. Test for Difference between Baseline Scenario and Hostile Village

An operation in a hostile environment in guerilla warfare would be an enormous drawback for the security forces. A high number of Blue casualties might be expected. However, if the terrorists are not willing to fight unless they have to, in other words, they prefer to hide or flee if they can, and if there are tunnels or caches in the villages, sometimes the security forces might not be able to find any of the terrorists. In those situations, the Blue forces might not suffer any casualties at all. But, the mission is not accomplished either. In the scenario that we developed, the terrorists do not want to fight, they are neither willing to surrender. They hide in caches built in the houses of the sympathetic villagers and receive information from villagers. As they are in caches, their sensor range and firepower are reduced. However, they can still cause high casualties because they can use high explosives (grenades) when discovered.

a. Difference between Blue Casualties for Both Scenarios

The bar chart in Figure 12, details the difference between mean Blue casualties of the scenarios. It can be seen that the search operations conducted in a hostile villages result in zero Blue casualties for 90 of the replications made. This number is 70 for Red casualties. The intersection of these cases gives us important information. We also see that in search operations in hostile environments Blue forces

are more likely to suffer high casualties. In 11 replications of the baseline scenario, the Blue forces receives more than five casualties while the number of replications that Blue receives more than 5 casualties is 29 for search operations in hostile environment. This same situation occurs in real-world operations if there are caches in the village. It is very difficult to find the terrorists if they hide. Even when the terrorists are found, Blue forces can receive very high casualties as they get in close contact. The analytical explanation of the comparison is done using Z-test.

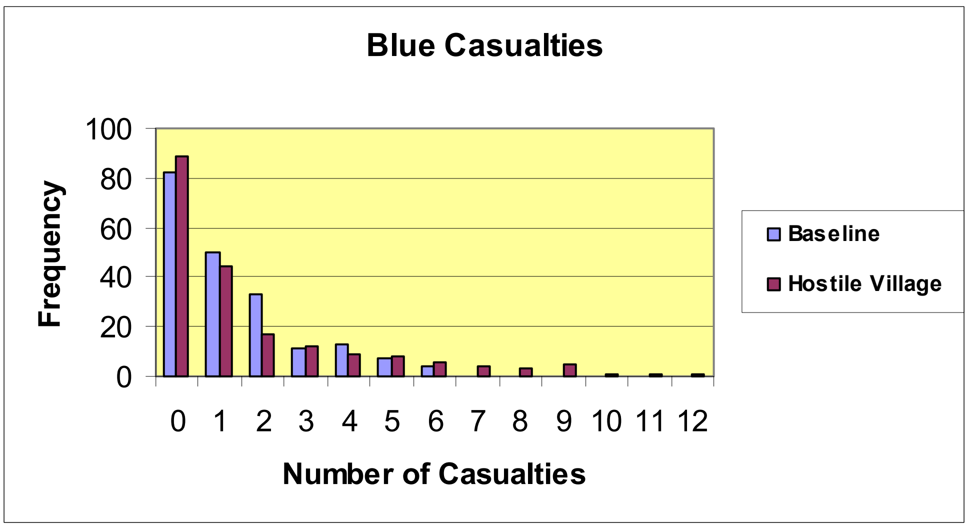

Figure 12. Comparisons of Blue Casualties for Both Scenarios

The null hypothesis suggests that there is no difference between both scenarios. Contrarily, the alternative hypothesis claims that Blue would receive higher casualties when search operations are conducted in hostile environments and suggests that the difference between both scenarios in terms of Blue casualties is expected to be less than zero.

The Z test for these scenarios;

- $H_a : X_1 - Y_1 < 0$
- $\overline{X} = 1.3 \quad \overline{Y} = 1.78$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 2.36 \quad s^2_y = 6.55$
- P-value = 0.0125

Notice that the variance of search operations conducted in hostile environment scenario is almost three times higher than the variance of the baseline scenario. This indicates that we can get extreme outcomes in a hostile village in terms of Blue casualties. For a *P-value* of 0.0125 the null hypothesis is rejected in favor of the alternative hypothesis. We conclude that when a skirmish occurs in a search operation the behavior of the villagers significantly affects the number of Blue casualties.

b. Difference between Red Casualties for Both Scenarios

The bar chart in Figure 13 indicates a difference between the numbers of mean Red casualties, in both scenarios. The y-axis represents the frequency of Red casualties for the 200 replications made. The x-axis represents the number of casualties. The support of the sympathetic villagers seems to affect the number of Red casualties significantly. It can be seen that for the 200 replications made the Blue forces were unable to eliminate the four terrorists when the searches were conducted in hostile environment.

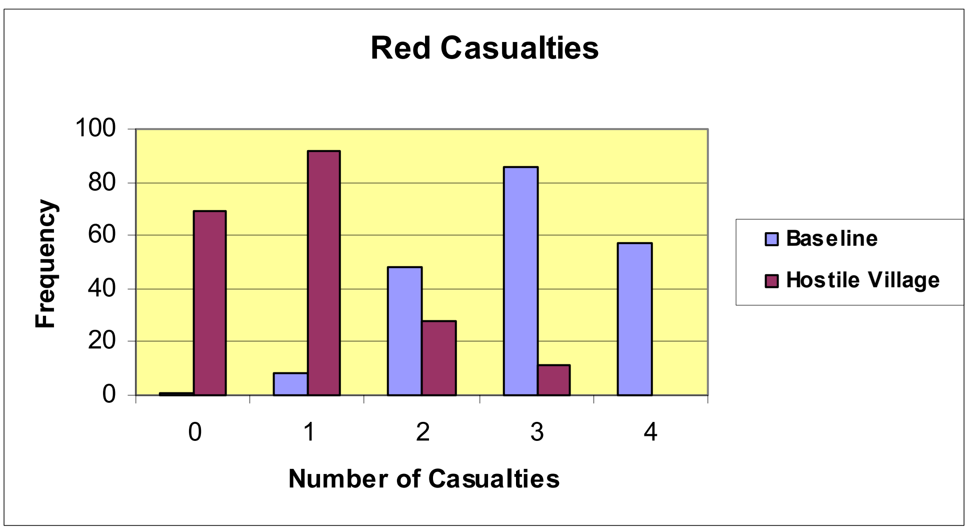

Figure 13. Comparisons of Red Casualties for Both Scenarios

The Z test for these scenarios;

- $H_a: X_2 - Y_2 > 0$
- $\overline{X} = 2.95 \quad \overline{Y} = 0.91$
- $m_x = 200 \quad m_y = 200$

- $s^2_x = 0.73$ $s^2_y = 0.699$
- P-value = 0

Looking at the mean Blue and Red casualties given above, we see that the mean number of Red casualties in the baseline scenario is around three times higher than the mean number of Red casualties of search operations conducted in a hostile village. This also indicates that the mean number of terrorists that escape in the hostile village is three times as many as the number of terrorists that escape in the baseline scenario. The Z-test is implied with the results obtained from the 200 replications. The alternative hypothesis suggests that the existence of sympathetic villagers would decrease the number of the Red casualties and the difference between both scenarios for Red casualties is greater than zero. The *P*-value strongly support the alternative hypothesis, the null hypothesis is rejected. We conclude that the support from the inhabitants of a village to the terrorists, in search operation would increase the number of Blue casualties and decrease the numbers of Red casualties.

4. Test for Difference between Baseline Scenario and Reserve Unit

In the scenario, the reserve unit has an observational task initially. The unit provides assistance to the search units when it receives information about the presence of terrorists. The expectation of a commander to employ a reserve unit would be to decrease the Blue casualties and to increases the Red casualties.

a. Difference between Blue Casualties for Both Scenarios

Examining the chart in Figure 14 we cannot say that deploying a reserve unit necessarily decreases the number of Blue casualties. The chart also indicates that Blue can sometimes suffer very high casualties when a reserve unit is deployed. This is because the number of soldiers increases in the area and when the reserve unit is dismounted close to the terrorists, the terrorists shoot at the soldiers. In real-world skirmishes when the terrorists detect helicopters in a close area they often shoot at them. This in turn, sometimes causes helicopter crashes and high casualties.

All of the soldiers in the reserve unit have night-vision goggles, so they have a high sensor range. The high sensor range has a slight positive effect on the mean Blue casualties. By positive effect, we mean that increasing the Blue sensor range somewhat increases the Blue casualties. Although it looks bizarre initially, when

observing the scenario it becomes clear; when the Blue forces have higher sensor ranges they can detect the terrorists most of the time, and they will try to eliminate them. In this case, the terrorists who are trying to flee will have to return fire in order to protect themselves. The analytical explanation of the comparison is done by a hypothesis test.

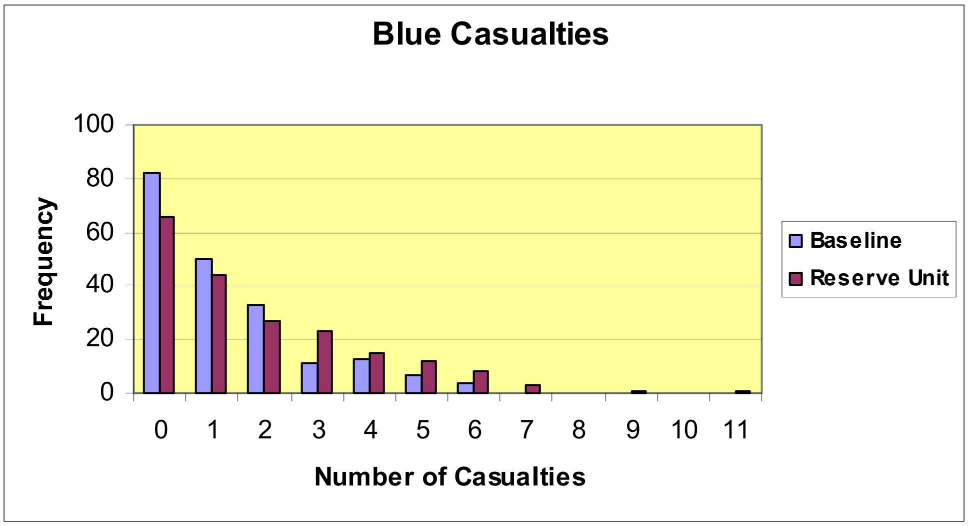

Figure 14. Comparisons of Blue Casualties for Both Scenarios

The alternative hypothesis suggests that the employment of a reserve unit would decrease the number of Blue casualties. Accordingly, the difference between the mean Blue casualties should be greater than zero. However, the results obtained from the test do not support this idea.

- $H_a : X_1 - Y_1 > 0$
- $\overline{X} = 1.3 \quad \overline{Y} = 1.88$
- $m_x = 200 \quad m_y = 200$
- $s^2_x = 2.36 \quad s^2_y = 4.166$
- P-value = 0.99

Note that for search operations where a reserve unit is employed the mean number of Blue casualties is around 40% higher than when a reserve unit is not employed (baseline scenario). Analytically the Z-test for the two populations indicates that the

reserve unit does not decrease the number of Blue casualties. In fact, if we test H_a: $X_1 - Y_1 > 0$ the *P*-value is 0.99. Thus, we conclude that contrary to our expectations there are more Blue casualties with reserve units in this scenario.

b. Difference between Red Casualties for Both Scenarios

The chart in Figure 15 shows that there is a significant difference between both scenarios, in terms of Red casualties. Almost in half of the replications, all four of the terrorists are eliminated when the reserve team is deployed. Visually inspecting the chart we can say that the reserve unit provides the necessary help to the commander to increase the Red casualties.

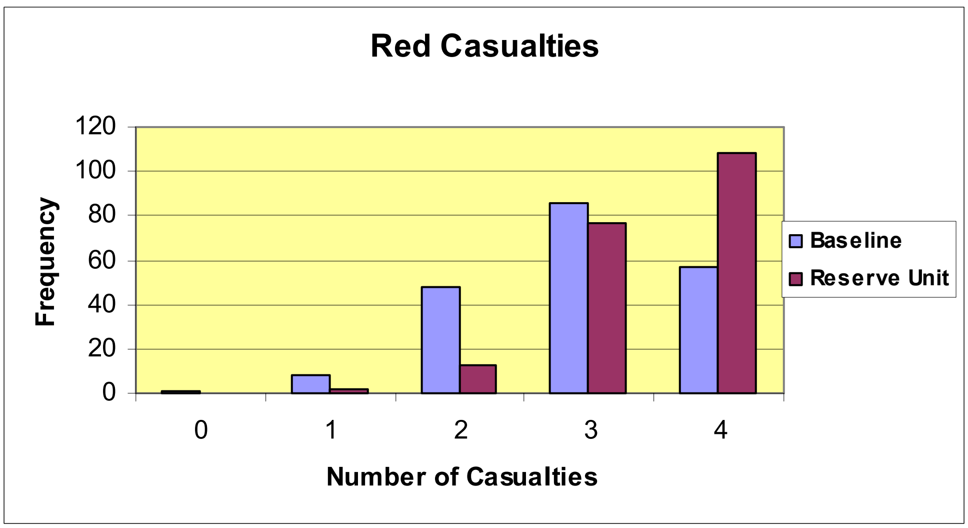

Figure 15. Comparisons of Red Casualties for Both Scenarios

Analytically, the alternative test suggests that the difference between both scenarios in terms of mean Red casualties is less than zero. In this case the null hypothesis is strongly rejected in favor of the alternative. It should be also noted that the mean number of terrorists that escape the reserve unit is almost half of the mean number of the terrorists that escape in the baseline scenario.

The Z test for these scenarios:

- $H_a : X_2 - Y_2 < 0$
- $\overline{X} = 2.95 \quad \overline{Y} = 3.45$
- $m_x = 200 \quad m_y = 200$

- s^2_x = 0.73 s^2_y = 0 .44
- P-value = 0

For this scenario a specific situation occurred. Although the number of Red casualties increases, the number of Blue casualties also increases when the reserve unit is deployed. From a commander's prospective, we would favor the scenario that decreases the Blue casualties while increasing the Red casualties. But we do not see that here. The risk that the commander would like to take becomes an important factor at this phase. If the commander does not want to take high risks, or suffer high Blue casualties, he may chose to not deploy a reserve unit. But, on the other hand, if the goal is definitely to eliminate as many terrorists as possible, the reserve unit might be employed. A third possibility is to look at the ratio of the Blue casualties to the Red casualties to decide whether the employment of a reserve unit is favorable. For the sake of this study we will conclude that the scenario resulting in a lower ratio of Blue to Red casualties will be favored. As we look at the exchange ratio, we expect that there are some zeros in the denominator. This is the reason why the bootstrap method is used to evaluate the difference between both scenarios. The following results are obtained from the implication of the bootstrap method: [Ref 15] the code implemented is developed by Associate Professor Thomas Lucas and is displayed in the Appendix D.

*** **Bootstrap Results for the Baseline Scenario** ***

> summary (out.con)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.3282051	0.4174594	0.4405477	0.4424048	0.4678155	0.5700000

*** **Bootstrap Results for the Reserve Unit** ***

> summary(out.res)

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
	0.5153645	0.5447278	0.5463647	0.5766558	0.7052023

We use the data obtained from the bootstrap method to conduct another hypothesis test. One might expect that a reserve unit contribute the security forces. Then the ratio of the Blue to the Red casualties should decrease whenever a reserve unit is employed and the difference of the ratio for the alternative hypothesis should be greater than zero.

For this case X_1 is the number mean number of Blue casualties for the baseline scenario, Y_1 is the mean number of Red casualties for the baseline scenario, X_2 is the mean number of Blue casualties for the scenario where the reserve unit is employed and Y_2 is the mean number of Red casualties where the reserve unit is employed.

- The null hypothesis $H_o = X_1/Y_1 - X_2/Y_2 = 0$
- $H_a = X_1/Y_1 - X_2/Y_2 > 0$
- $\frac{\overline{X_1}}{\overline{Y_1}} = 0.44 \quad \frac{\overline{X_2}}{\overline{Y_2}} = 0.55$
- P-value = 0.96

The *P*-value does not support the alternative hypothesis test. The null hypothesis is not rejected. We cannot conclude that the reserve unit is providing a satisfactory contribution to the security forces. As the number of Blue casualties also increases the deployment of the reserve unit is not favored in this case.

C. ANALYSIS OF THE BASELINE SCENARIO WITH THE REGRESSION TREES

This section looks at the analysis of the mean Red casualties and mean Blue casualties as a function of the 16 factors described for the baseline scenario. Regression trees are used to explore the data set obtained from the simulations of around three thousand search operations. Regression trees are preferred here as they are easy to understand and to interpret. They also provide a satisfactory treatment of missing values. In addition, it is easy to obtain and visualize general interaction forms. Moreover, the results are invariant to monotonic transformations in the response. [Ref 16] Finally they are also robust to outliers [Ref 14]

1. Regression Trees for Blue Casualties

This subsection examines the mean Blue casualties according to the sixteen factors defined for the baseline scenario. The factors that appear on the regression tree are:

- **SearchT_MSpeed (Movement Speed):** This parameter is the speed of the search unit that enters the village.
- **Ter_OC3_Stealth (Stealth):** The stealth parameter in MANA represents the difficulty in detecting an entity when it enters the sensor range. This parameter affects the Red agents' visibility when they enter the sensor range of other agents.

- **Ter_OC3_OT3 (Enemy Threat3):** This parameter affects the propensity of the terrorists to move toward or move away from the security forces.
- **SearchT_OC3_Stealth (Stealth):** This parameter affects the search unit's probability to be seen by other agents.
- **TC_ComRel (Communication Reliability):** This parameter affects the probability that information is sent to the desired destination.

The residual mean deviance of the tree model in Figure 14 is 0.15.

> The residual deviance is the sum of the squared variation of the observations in a tree model depending on the type of the tree (classification/regression). The residual mean deviance is calculated by dividing the residual deviance by the number of observation minus the number of terminal nodes, in other words, by dividing the residual deviance to the degree of freedom. [Ref 16]

Looking at the tree we can see that there is a lot of variation in the number of Blue casualties. The mean Blue casualties range from .66 to 2.1.

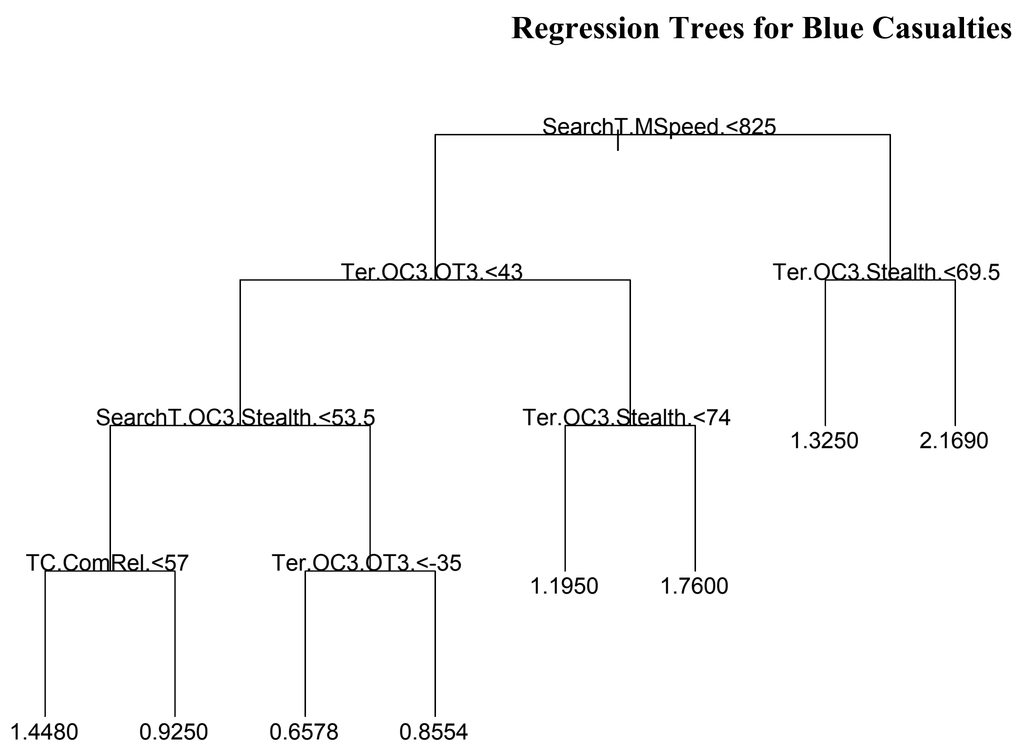

Figure 16. Regression Tree Model of MOE 1

The regression tree model in Figure 16 indicates that the speed at which the search team is inserted is the main factor affecting the Blue casualties. An initial observation of the figure gives the impression that a lower speed is better for the Blue search unit. Looking closely at the scenario with several replications at different speed levels, it is realized that the slower the speed of the Blue search teams the higher the Blue casualties. In the scenario, the search unit is inserted in two components into the village. One of the teams comes from the north and the other from the south. The team coming from the north is better equipped than the other one and has a higher sensor range. In addition, the team coming from the south comes from an area with lower altitude. This fact affects the sensor range of the dogs, which are the main source of information for the Red forces. In other words, the dogs detect the Blue forces coming from the north before they detect the other team. As soon as the terrorists (Red forces) receive any information about the presence of the Blue forces they try to flee. In this case, when the speeds for both search teams is the same, the terrorists detect the search team coming from the north first and try to flee from the south of the village. This causes the terrorists to run into the Blue team coming from the south—which is poorer in terms of equipment and this causes higher Blue casualties. When the speed of the team coming from the south is higher, the terrorists detect both search teams almost at the same time and try to evade both teams. In fact, in real-world operations one of the times that the troops are more vulnerable is when unarmored vehicles carry them. The enemy can ambush, fire at or attack the Blue forces easily as the troops are not positioned and exactly ready for combat. In the scenario, Red forces are trying to evade and when they run into the search team coming from the south, they come in close contact and engage them. This increases the Blue casualties and also the Red casualties. In Figure 17, the search teams and the road that they follow are shown and in Figure 18, the shape of the terrain is displayed in a two-dimensional plot for clarity.

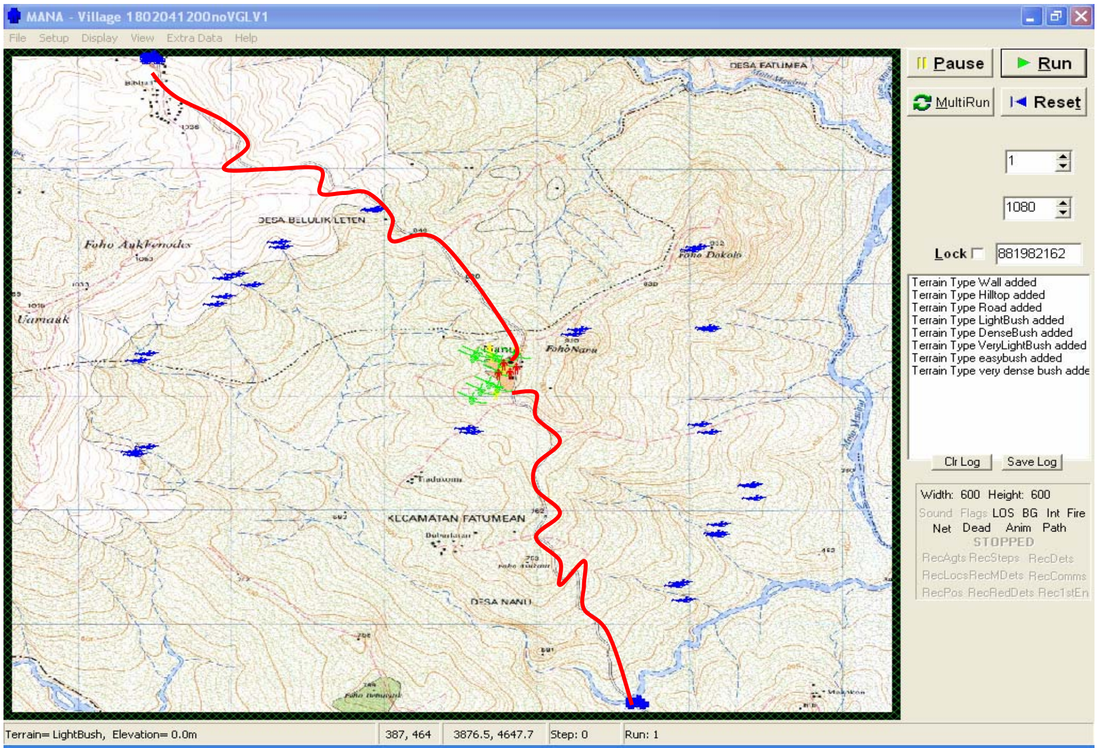

Figure 17. The Roads Followed by the Search Teams

Looking at Figure 18, we can see that the dogs can detect the trucks coming from the north first, if both teams enter the village at the same speed. If the movement is synchronized and the trucks coming from the south are faster than the ones coming from the north, detecting both search teams almost at the same time, the terrorists try to move away from both. In this case, the troops dismount the trucks and start pursuing or searching the enemy. It is important that the Blue forces dismount the trucks first and then contact the terrorists. The Blue receives higher casualties if they contact the terrorists before dismounting the trucks.

The lesson learned from this case is that the shape of the terrain should be evaluated carefully in the planning process of any search operation. Still, the high speed is of high value but synchronization of the speeds of the search team inserted into the village also has a high importance.

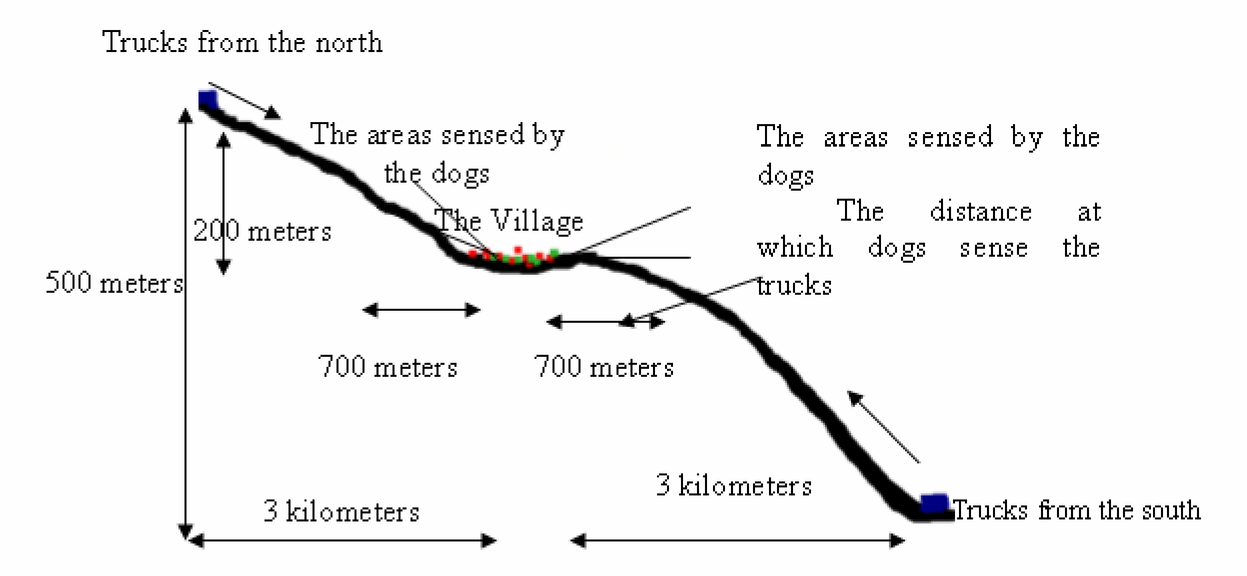

Figure 18. The Two-Dimensional View of the Area

In Figure 16 we see that the other factors affecting the Blue casualties are the stealth of the Red forces, the stealth of the Blue forces, the Red propensity to move toward the Blue and the communication reliability of the Blue forces. The stealth of the Red forces and the Red propensity to move toward the Blue initially seem to be factors that cannot be affected by the Blue forces. As there are a lot of Blue troops in the area doing the search operation, the variability of the mean number of Blue casualties is also high. The tree indicates that the lowest mean casualties received by the Blue forces is around .65. This happens when the speed of the search teams are set appropriately, the Red propensity to move toward the Blue is less than 35 (terrorists are not very aggressive), and the Blue search team stealth is over 53.5 (the probability of spotting a member of the Blue search team if in range is reduced more than a half per time step). The Blue receives the highest casualties when the Red stealth is over 69.5 (the probability of detecting the terrorists is less than one third of what it otherwise would be per time step). Two of the factors appearing on the tree are the Red factors and at a first glance it seems that we cannot change them. In fact, the Red stealth can be affected by focusing on increasing the Blue ability to detect the Red forces and the Red propensity to move toward the Blue can be affected by making the Blue deterrent forces. On the other hand,

the stealth of the Blue forces (which is closely related to Blue training) and the communication reliability are important factors to consider by the Blue forces.

Figure 19 (a truncated regression tree) indicates that when the speed of the Blue forces is set accordingly just two of the factors can explain a great proportion of the variability of the Blue casualties. For example, if the speed is over 825 (over 23 km/hr) and the Red propensity to move toward the Blue is less than 43 (a terrorist that does not have a strong desire to move towards the blue), the mean Blue casualties decrease to 0.9051. If the Red propensity to move toward the Blue is over 43 (a terrorist with a strong desire to move towards the blue) the mean Blue casualties increase almost by half and become 1.412. On the right hand side of the regression tree, we can see that the Red stealth affects the Blue casualties more severely. If the stealth is less than 69.5 (i.e., the terrorists are not too difficult to spot if in range, with less than a two thirds reduction in detection probability), the Blue casualties average 1.325. If it is over this value, the Blue casualties average 2.196. The residual mean deviance for this tree is .2. This is again because of the high variability of the mean Blue casualties. It should be noted that just by varying two of the variables, the mean Blue casualties increase from .9 to 2.16. This fact reveals the importance of the factors displayed in the tree model shown in Figure 19. In fact the same three factors are found to be the most important factors in the linear regression model and are displayed in Table1.

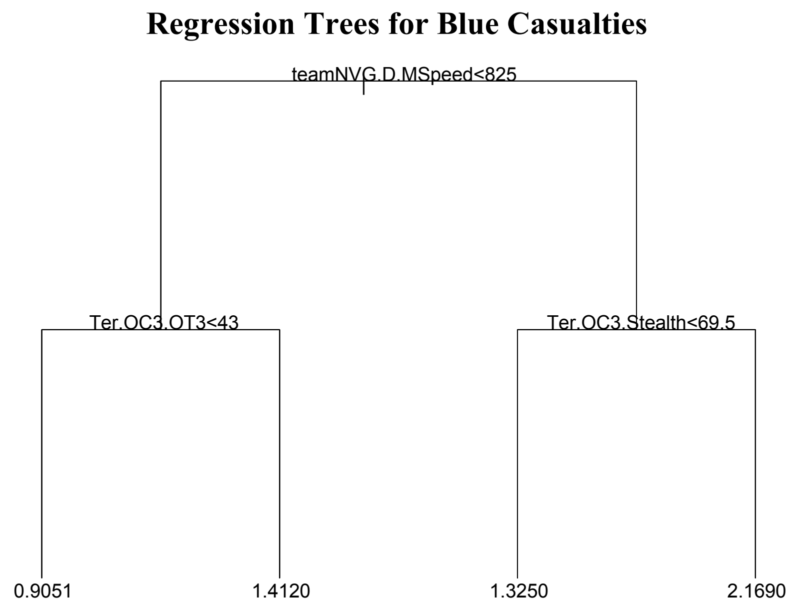

Figure 19. Regression Tree Model of MOE 1

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
SearchT_MSpeed	1	1	4.934841677	75.49629	5.13E-11
Ter_OC3_Stealth	1	1	4.060424099	62.11891	6.98E-10
Ter_OC3_OT3	1	1	3.032083611	46.38671	2.42E-08

Table 1. The Most Important Three Factors Obtained From the Linear Regression of the Data Set for the Blue Casualties

Figure 20 shows a leverage plot that displays the partial effect of the Blue search team movement speed on the mean number of Blue casualties. The partial effect is the impact of the factor on the response when the response has been regressed on all other factors. The x-axis on the plot is the Blue search team initial movement speed and the y-axis is the mean number of Blue casualties. It is obvious that increasing the Blue movement speed increases the Blue casualties. Again this is for the reasons explained in the discussion of the regression trees. The Leverage plots show the partial effect of the variables on the model. The distance from each point to the horizontal line is what the error would expect to be if the effects were not included. The center red line is the line of

fit. The distance of each point to that fit gives the residual error for that point. The steepness of the confidence curves (the lines around the center line) indicates the level of significance of the effect. [Ref 22]

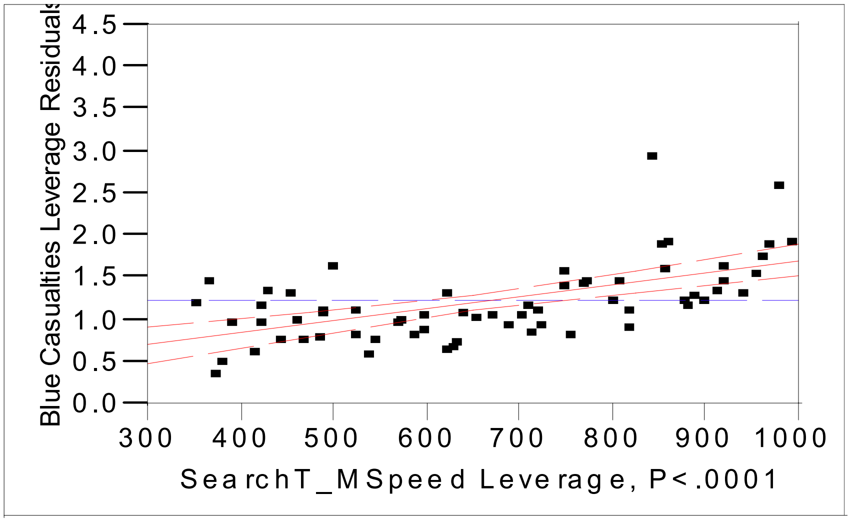

Figure 20. Leverage Plot for Blue Movement Speed (Search Team Initial Movement)

Figure 21 displays the leverage plots for the Red stealth and Red propensity to move toward (Red aggressiveness) the Blue. The y-axis represents the mean number of Blue casualties for both graphs and the x-axis represent the Red stealth parameter and Red aggressiveness. When both of the factors increase, the mean number of Blue casualties also increases.

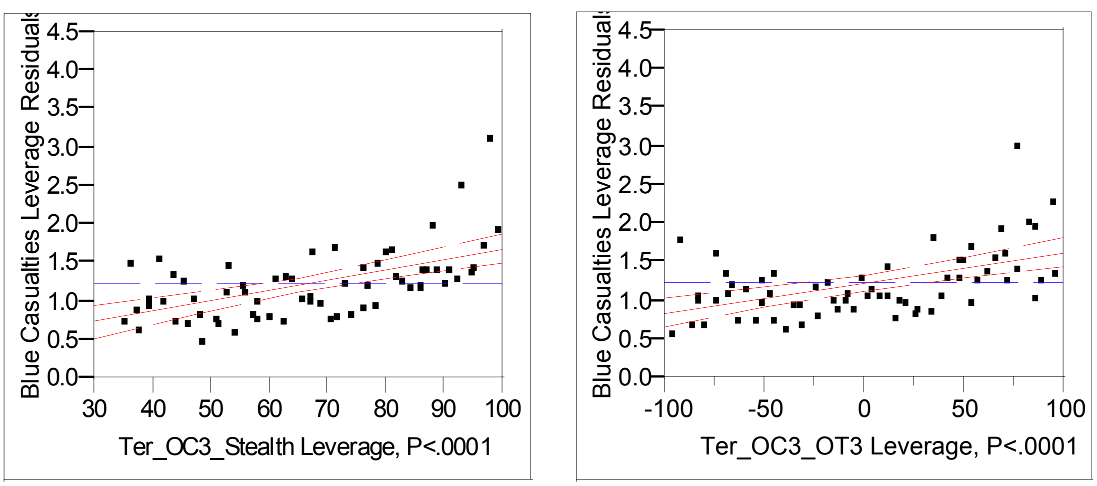

Figure 21. Leverage Plots for the Terrorists' Stealth and Terrorists' Propensity to Move Toward the Blue Forces (Aggressiveness)

2. Regression Trees for Red Casualties

This subsection examines the analysis of the baseline scenario in terms of Red casualties as a function of the sixteen factors stated previously. The factors that appear on the tree model are:

- **Ter_OC3_Stealth (Stealth):** This parameter affects the Red agents' visibility when they enter in the sensor range of other agents.
- **SearchT_ITR (Inorganic Threat Rate):** The inorganic threat rate is the number of time steps that must pass for a threat on the Inorganic Situational Awareness map to disappear. [Ref 6]
- **Ter_OC3_OT3 (Enemy Threat3):** This parameter affects the propensity of the terrorists to move toward or move away from the security forces.
- **SearchT_MSpeed (Movement Speed):** This parameter is the speed of the search unit that enters the village.
- **SearchT_NT (Non-target Classes):** The villagers are defined as agents that cannot be targeted. This factor is defined to explore the effects of the presence of civilian in the area when a skirmish occurs.

The residual mean deviation of the tree model for the Red casualties is .012. This means that the predicted values are quite precise. Observing the tree, we can see that there is little variation in the mean Red casualties. The number of Red casualties ranges from 3.008 to 3.788.

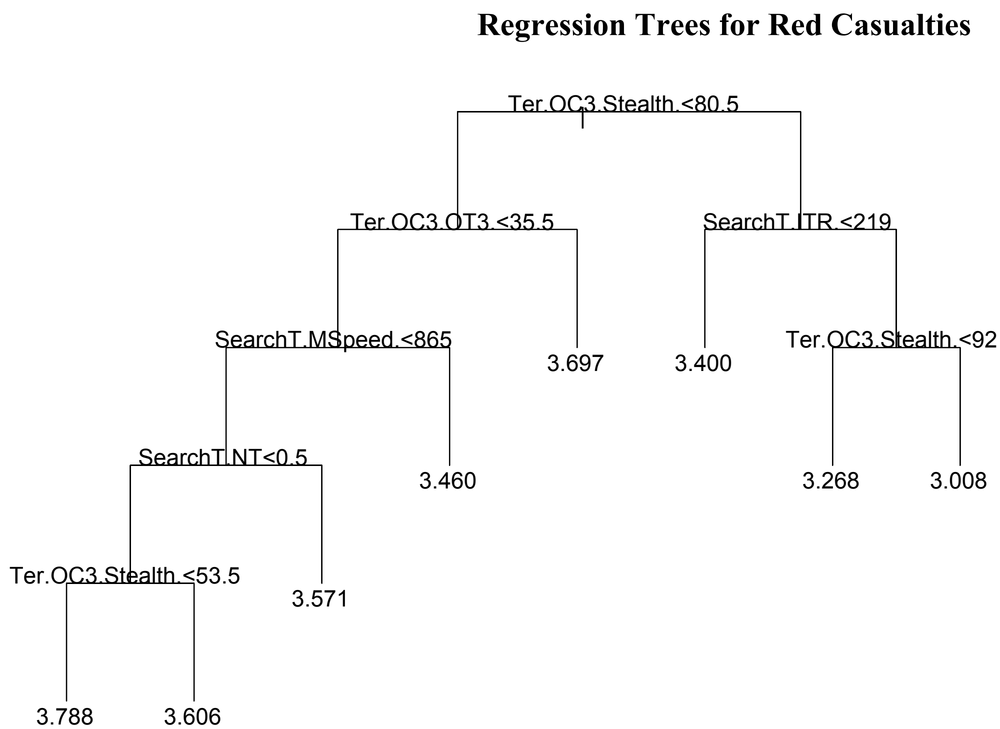

Figure 22. Regression Tree Model of MOE 2

The Red stealth is the main factor affecting the Red casualties. In Figure 22, the nodes emanating from the first node indicates interaction between the factors stated. If the Red stealth is over 80.5 (i.e., it is difficult to detect the terrorists, less than one fifth of the probability of detection without stealth) and the inorganic threat rate of the Blue team is less than 219 (36.5 minutes), then the mean Red casualties is 3.4. When the inorganic threat rate is over 219 and the Red stealth is over 92 (i.e., it is very difficult to detect the terrorists, less than one tenth of the probability of detection without stealth), the Red casualties decrease to 3.008. This is the best result that the Red can have. In other words, setting the variables as stated above create the case in which the terrorists receive the least casualties. The inorganic threat rate is the amount of time that a detected entity will stay on the situational awareness map. In a real-world environment this is the amount of time that a detected enemy is assumed to stay at the same location. Replicating the scenario many times, it is observed that when the inorganic threat rate is

high, the Blue search team gathers on a small area and moves toward the point where the enemy is detected and assumed to stay. This reduces the probability of contacting the other Red forces that could be around. Contrarily, when the threat inorganic threat rate is low, the search team spreads throughout the search area and detects more enemies—which increases the number of Red casualties. In Figure 23 we can see that although the terrorists (agents in red colors) are killed by the snipers, the Blue search team is still searching the area. This is true because the terrorists killed by the snipers still look alive to the search team (the blue moving agents) inorganic situational awareness map. And, as we can see, the search team is searching a small proportion of the area and simultaneously the fourth terrorist is escaping the Blue forces.

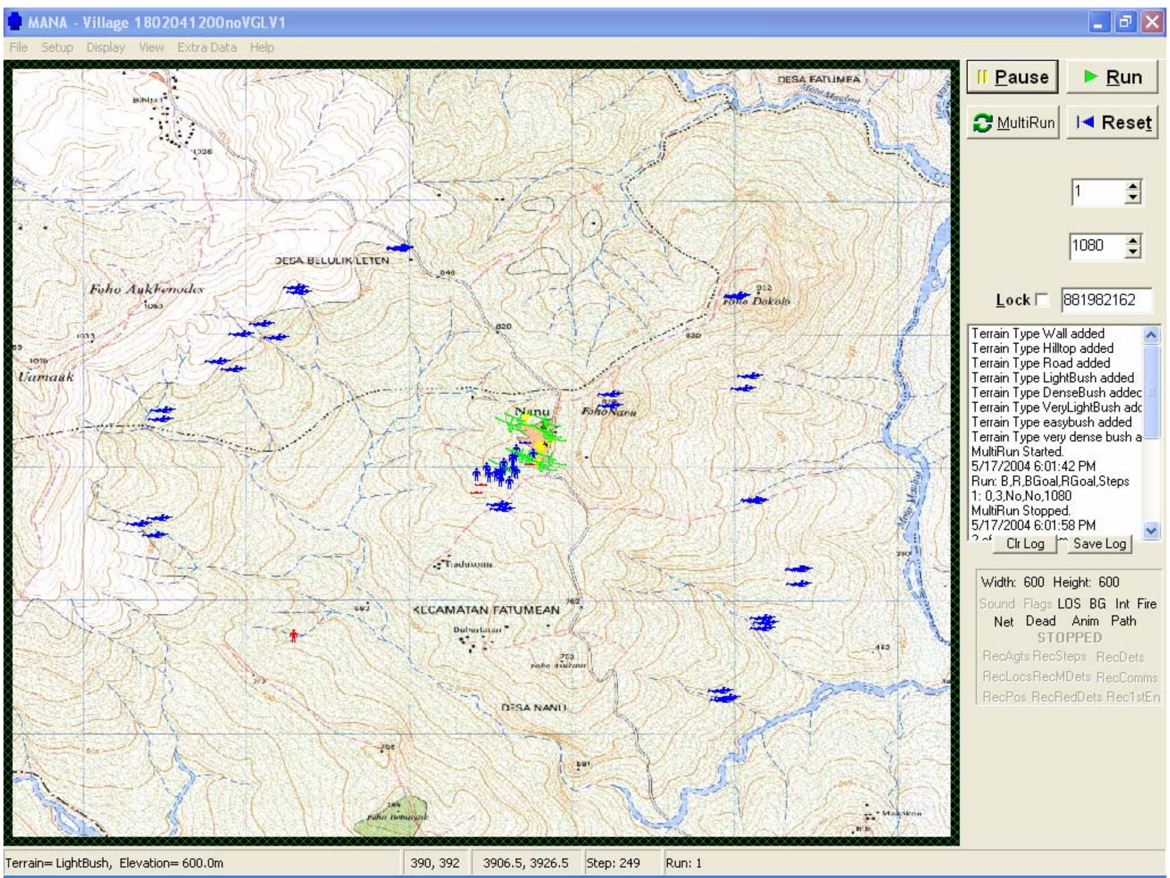

Figure 23. Blue Search Team Searching the Terrorists

In Figure 24, the search team (Blue moving agents) is gathered again to find the terrorists. Unfortunately, by this time the terrorist is already gone. We can see the

terrorist (red agent) evading the Blue forces. But as the inorganic threat rate of the Blue search team is high, the team is still searching the area according to the stale information it received. This is also the case in the real world. When information is received about the presence of terrorists at a specific location, we can move to that point and search the area although the enemy has already gone when we reach that point. Sometimes security forces receive stale intelligence or information and operations are conducted according to this information. A question still remains to be answered: how long should we assume that the enemy is still there or how should we define the length of the inorganic threat rate?

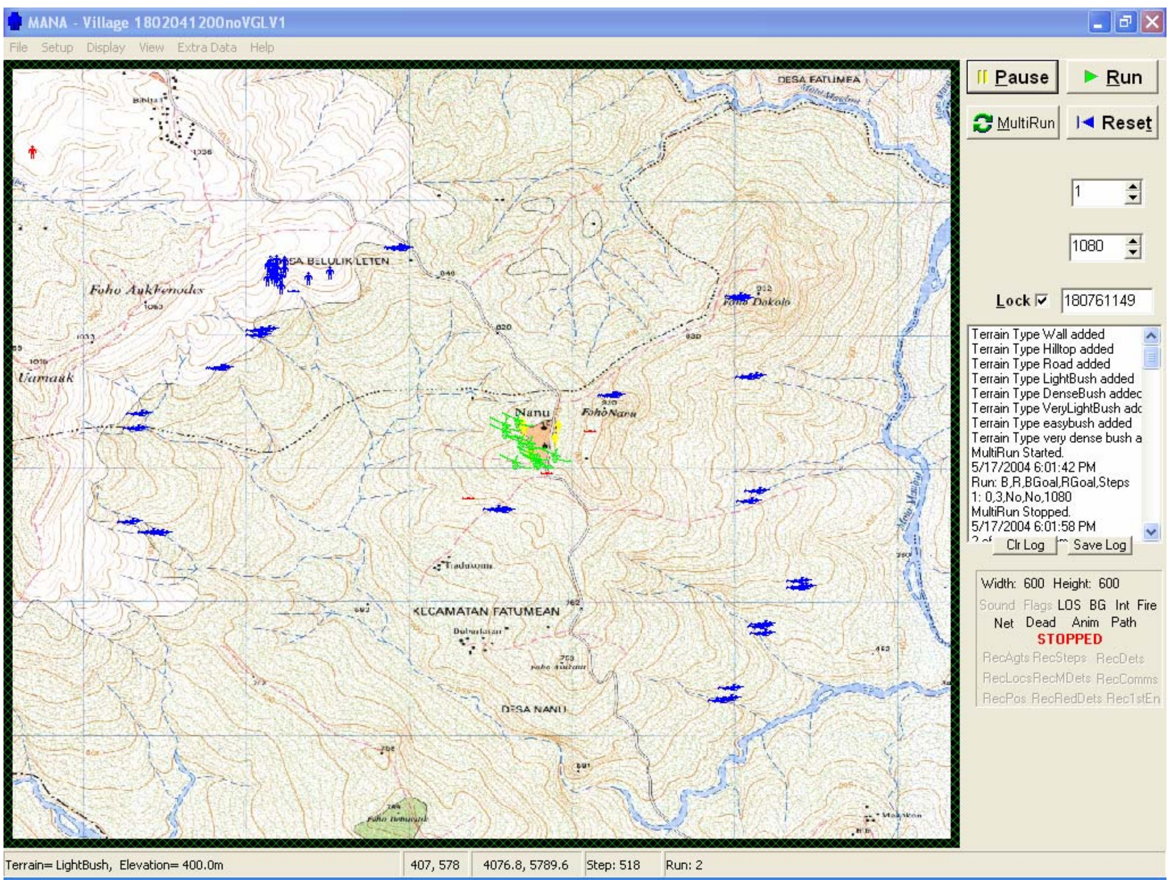

Figure 24. Blue Search Team Searching the Terrorists

Looking at the tree model in Figure 22, the left-hand side of the regression tree shows that there are interactions between Red stealth, Red propensities to move toward the Blue, Blue movement speed, and the presence of the villagers. Examining each node

differently, it is obvious that increasing aggressiveness of the Red increases the Red casualties. If the speed of both Blue search units (the unit coming from the north and the unit coming from the south) is decreased equally the Red casualties increase. This is because when the speed of the Blue search teams coming from the north and from the south are set to a lower and equivalent level, the terrorists first detect the team coming from the north and try to flee toward the south of the village and encounter the team coming from the south. This in turn increases the number of Red casualties as well as the Blue casualties. Beyond this, an important factor affecting the Red casualties is the presence of the villagers in the area. When the Red stealth is less than 80.5, Red aggressiveness is less than 35.5 (terrorists do not have a strong desire to move towards the Blue), the speeds of the Blue search teams are less than 860 (less than 24 km/hr) and with the presence of the villagers (the Blue try not to shoot the villagers or accidentally kill any villagers), the mean Red casualties decrease to 3.46. It is obvious from the tree that when the Blue search team tries to avoid targeting the villagers (Search_NT >0.5), the Red casualties decrease. The interesting result is that although a few villagers are defined in the scenario, from the tree we can see that the presence of civilians in the area decreases the number of Red casualties. This is because the Blue forces are concerned about damaging civilian property and injuring civilians. This fact reduces the Blue firepower and with reduced firepower the number of Red casualties declines. Walking through the tree, we see that if the villagers are not defined as non-targeted agents (Search_NT<0.5) and Red stealth is over 53.5 (the probability of detecting the terrorists if in range, is less than a half), the Red casualties average 3.606. If Red stealth is less than 53.5, the Red casualties average 3.788. This is the highest number of casualties that the Red can receive if the factors are set as shown in the tree. The fit of the three is quite good. The residual mean device of the tree is 0.012. This signifies that the predicted values of the tree are quite precise.

In Figure 25 a truncated version of the regression tree for Red casualties is displayed. Here we want to observe the variability of the Red casualties according to the most two important factors affecting this number. The residual mean deviance is 0.02. This shows us that there is a low deviance between the responses (predicted outcomes) in the tree model, and this indicates that we can predict the number of Red casualties with

high precision just by varying the two factors: the Red stealth and the inorganic threat rate of the Blue search team. If the value of the Red stealth is set to be less than the 80.5, then the mean Red casualties is 3.626. On the other hand, if the value of the Red stealth is set to be over 80.5 (i.e., it is difficult to detect the terrorists, less than one fifth of probability of detection) and the inorganic threat rate of the Blue is less than 219 (36.5 minutes), the average Red casualties decrease to 3.4. If the stealth value of the Red forces stays over 80.5 and the inorganic threat rate for the Blue search team is over 219, then the mean Red casualties decrease to 3.138.

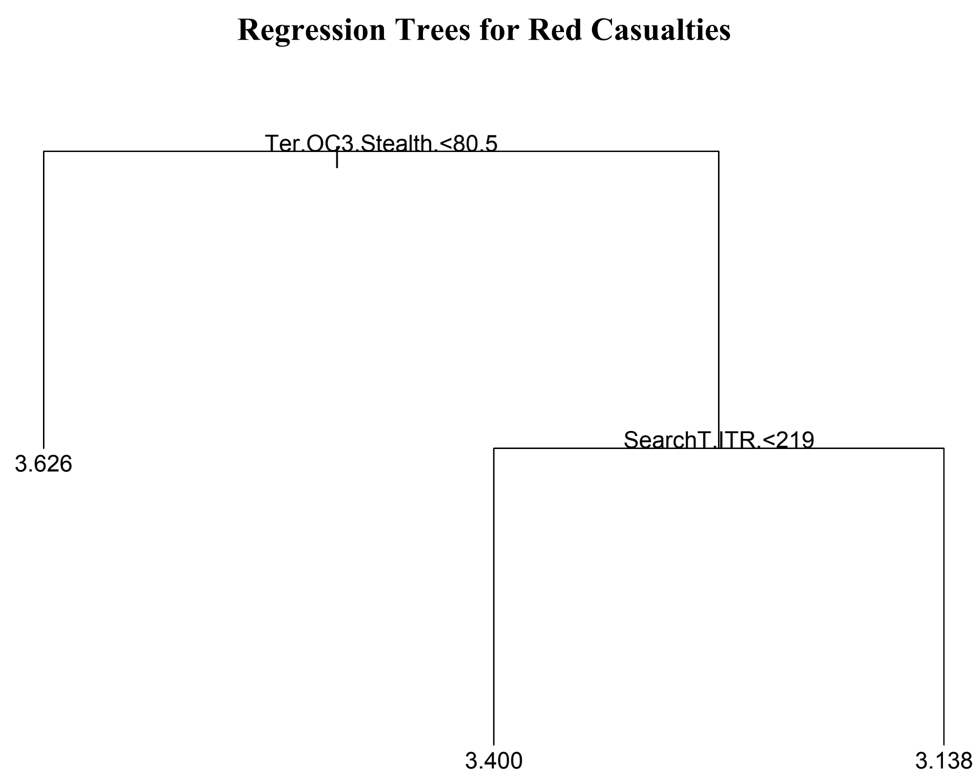

Figure 25. Regression Tree Model of MOE 2

Figure 26 displays the leverage plots for the Red stealth and Blue search team inorganic threat rate. Those factors are the first two factors appearing on the regression tree for Red casualties. The graphs show the effect of both factors on the Red casualties. The y-axis represents the mean number of Red casualties while the x-axis sequentially

represents the Red stealth and Blue search team inorganic threat rate. The graphs indicate that both factors negatively affect the Blue casualties. In other words, increasing Red stealth or Blue search team inorganic threat rate decreases the number of Red casualties. In leverage plots, the steepness of the fit line indicates the level of significance of the factor to the response variable. It should be also noted that the effect of the Blue search team inorganic threat rate is not as significant as the effect of the Red stealth. The leverage plots are given here in order to amplify the results obtained from the Regression trees.

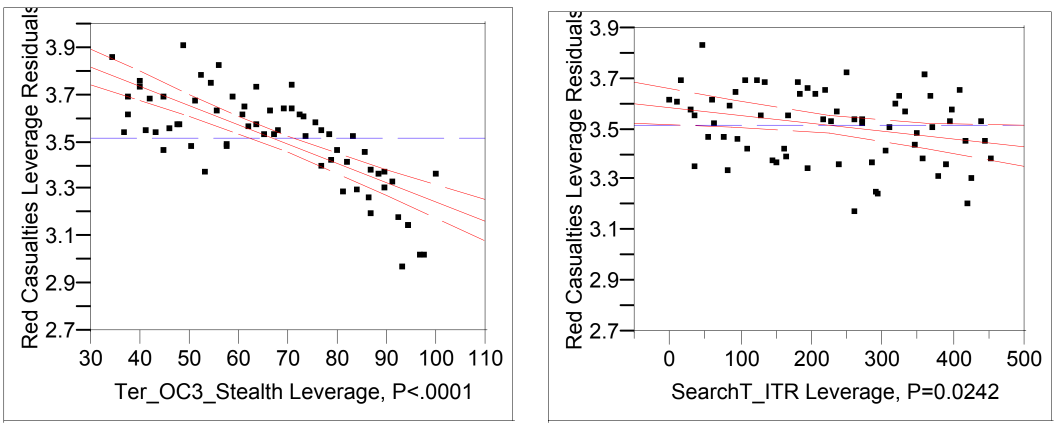

Figure 26. Leverage Plots for the Red Stealth and Blue Search Team Inorganic Threat Rate

This chapter explained the results obtained from the analysis of the data set and the comparisons of the scenarios. The next chapter will discuss the conclusions drawn from the analysis.

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VI. CONCLUSIONS

This chapter contains the conclusions drawn from the analysis of the sixteen factors data set as well as the conclusions obtained from the comparisons of the five scenarios.

- The proficiency level of the soldiers and the equipment used significantly affect the outcome of a search operation. Thus, whenever possible, well-trained professionals should be used in search operations.
- The employment of village guards is highly beneficial in decreasing the Blue casualties, at least as modeled in the scenario. In this study, the village guards are only used to observe the Red force's activities and to join the Blue search team when they come into the village. The important point is that the village guards have a visibility of 150 meters and this is not extremely high. We want to emphasize that even a relatively small help (the initial location of the terrorists) provided from the village, either from village guards or from villagers, is highly important to the Blue forces.
- The support of the local people is critical to the Blue forces. For a village search operation, the support of the villagers to the terrorists highly affects the number of Blue casualties.
- Intelligence is a key factor for search operations. The Blue forces should have information about the presence of any kinds of caches or tunnels built in the area.
- For this specific case, the employment of a reserve unit did not seem to be very beneficial. We conclude that if appropriate cordon and search techniques are implemented, as modeled in the scenario, the employment of a reserve might not be favored. In fact, if the commander is concerned more about the number of Blue casualties, he might not want to use a reserve unit in this case. But, if the commander is determined to eliminate the Red casualties at all cost, he might want to use a reserve unit.
- The speed of the Blue forces inserted into the village is the most important factor affecting the Blue casualties. The speed might have hazardous effects if considered independent from the shape of the terrain. Terrain and speed should be considered together to make the speed an advantageous factor for the Blue forces. In the scenario, the search team divides into two components and is inserted following the roads from the north and from the south. Synchronization becomes an important factor. If the speed of the two search unit is synchronized then the Blue casualties decrease.

- The Red stealth is the most important factor affecting the Red casualties, and it is also an important factor affecting the Blue casualties. The Blue forces should focus on decreasing the Red stealth by using appropriate equipment like night-vision goggles.
- Red aggressiveness is an important factor affecting both the Red and the Blue casualties. The casualties of Blue forces decrease when the Red avoids contacting the Blue.
- Reliable communication has an important impact on Blue casualties. The capability of the communication devices should be increased and good communication techniques should be implemented.
- The presence of the civilians decreases the firepower of the Blue forces who are concerned about civilians' life and property. The civilian component should be included in the planning process of search operations.
- In order to find if an individual fault is critical to the results of the operation, we varied the stealth value of the sniper placed on the hill close to the village. When the stealth value is less than 100, the terrorists detect them immediately and run away. In this case the other sniper team and the forces positioned in the outer cordon team targets them. This indicates that the individual faults may not always be critical.
- All of the questions and factors explored in this study are based on concerns personally experienced in real-world situations. MANA (Map Aware Non-Uniform Automata) proved to be efficient at exploring the factors affecting the non-linear nature of a search operation and the emergent behavior in low-intensity conflicts.

VII. RECOMMENDATIONS

A. CHAPTER OVERVIEW

This chapter details the recommendations both to the developers of the model and the analyst interested in studying in this area. The recommendations stated in this chapter concern either the limitations faced in this study or the features that may be considered by the developers to improve the ability of the model to tackle other problems. The recommendations for the analyst consist of possible areas of study as well as some recommendations for modeling.

B. MODEL DEVELOPERS

This section includes the recommendations to the developers, either about the problems faced or about the features that might help the model deal with other real-world problem.

- MANA does not provide the ability to change the number of agents between states. In the scenario called Reserve units, the reserve unit is carried by helicopter and whenever a terrorist is detected, a state change representing the unit dismounting the helicopter is triggered. In order to represent the seventeen soldiers dismounting the helicopter seventeen helicopters were used. Because in MANA it is not possible to change the number of agents changing between states. This causes a visualization problem. Also, a high distance occurs between helicopters when they are flying. This in turn affects the state change and some of the helicopters keep flying instead of performing the state change.
- No kind of formation can be defined in MANA. Conventional military tactics requires the uses of appropriate formation techniques for the conducted operation. In our scenario, during the search operations when the search unit receives any information indicating the presence of Red agents, the unit moves toward the area without using any formation. In this case, as the search team gathers to move to the waypoint some areas are not searched. If any formation could have been used it would be possible to move toward the waypoint, to spread the soldiers, and to search the area at the same time.
- In MANA it is difficult to associate the names and the features that they represent. From a military perspective, it would be easier to understand and to associate MANA's features if the names would have been chosen accordingly.

- In MANA, only a waypoint and an alternative waypoint can be defined for any entities. But sometimes it becomes necessary to have more alternative waypoints. For example, let's say that in a scenario a reserve unit is supposed to assist one of the four units located in different areas when they contact the enemy. The reserve unit would choose the unit that is in the most critical situation. The same situation could be represented in MANA if it were possible to define more alternative waypoints.
- Although some of the agent-based models provide the ability to define a hierarchy, MANA does not have such a property. This becomes important for maneuvers. If the idea is to create a scenario where a maneuver is to be represented, a unit should suppress the enemy with its firepower while the other is maneuvering. This requires leadership. If hierarchy or leadership can be incorporated in MANA these scenarios can be created easily.
- The manual of MANA includes the necessary detail of the model, which makes it easy to understand. But learning the technical details of the model does not exactly mean learning modeling. Due to their nature, agent-based models have some characteristics that a beginner needs to understand. A section including modeling techniques might help to save time for the beginner. An important assistance provided by Mitre and the Training & Doctrine Command (TRADOC) Analysis Center (TRAC), Monterey, for this study helped to clarify the modeling techniques.

C. ANALYST

This section gives some recommendations to the analyst intending to study this area.

- A study including civil-military relations can be done in an area where a low-intensity conflict exists. The analyst can initially create a scenario in which local people are sympathetic to the insurgency to explore the effects of a good civil-military relationship. The refueling feature incorporated in MANA allows modeling propaganda.
- A stepwise method of developing a scenario is highly important. The developers must make sure that each entity defined in the scenario clearly plays the role that it is assumed to play before adding new ones.
- Before developing scenarios, it should be understood that all agent-based models are initially developed for different purposes. Great care should be given for choosing the appropriate model.
- The analyst should be aware that there are several statistical packages that he/she can use instead of just using one—because different statistical packages have different strengths and weaknesses.

- The variable selection procedure is one of the most important steps in the analysis. Analysts should ensure that they choose the variables important to them or the variables that can explain the variability of the MOEs chosen.
- From experience, defining different single-shot kill probabilities for different ranges does not become very useful when the objective is to explore these probabilities in a data set. If the purpose is to explore the effect of the variability of the probability of kill, then to define a single range and a single probability of kill for this range is recommended. This is true because with agent-based models the idea is usually to find the relative importance of a factor not to predict the exact outcome.

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APPENDIX A. DESCRIPTIONS OF THE PERSONALITY PARAMETERS

Description	Controls propensity to move toward/away from
Agent SA – Response by agent to information it has obtained in the current model step	
Enemies	Agents of enemy allegiance within sensor range
Enemy Threat 1	Agents of enemy allegiance threat 1 within sensor range
Enemy Threat 2	Agents of enemy allegiance threat 2 within sensor range
Enemy Threat 3	Agents of enemy allegiance threat 3 within sensor range
Ideal Enemy	Agents of enemy allegiance within sensor range that are have the ideal enemy class. This class is defined in the “En. Class” box to the right.
Friends	Agents of same allegiance within sensor range. The squad only/all friends toggle box allows the user to select what friends are referred to for this and the next weighting.
Injured Friends	Injured agents of same allegiance within sensor range. The toggle box for non-injured friends applies similarly here.
Neutrals	Agents of neutral allegiance within sensor range
Next Waypoint	The next waypoint agent's squad has been assigned
Alternate Waypoint	The alternate waypoint agent's squad has been assigned
Easy Going	Areas with easy going within 5 pixels of agent
Cover	Areas with protection from fire within 5 pixels of agent
Concealment	Areas which improve stealth within 5 pixels of agent
Centre	The centre line (defined as line between the current and immediately past goal)
Squad SA – Response to contacts on squad’s SA map	
Enemy Threat 1	Enemies which are of Threat Level 1
Enemy Threat 2	Enemies which are of Threat Level 2
Enemy Threat 3	Enemies which are of Threat Level 3

Description	Controls propensity to move toward/away from
Squad Friends	Agents of same squad
Other Friends	Agents of same allegiance but not in same squad
Neutrals	Neutral agents
Unknowns	Contact detections that have not been classified
Inorganic SA – Response to contacts on squad's Inorganic SA map	
Enemy Threat 1	Enemies which are of Threat Level 1
Enemy Threat 2	Enemies which are of Threat Level 2
Enemy Threat 3	Enemies which are of Threat Level 3
Friends	Agents of same allegiance
Neutrals	Neutral agents
Unknowns	Contact detections that have not been classified

Table 2. Personality Parameters (MANA Version 3.0)

APPENDIX B. TABLE OF DESIGN REPRESENTING THE RANGES OF PARAMETERS

Identifier	N Rows	Ter_OC3-E	Ter_OC	Ter_OC3ss	Ter_OC3_ Stea	Ter_OC3_ OT3	Ter_OC3_ SR	SniperStealth	SearchT_Fw_Stealth
I0E0	50	81	-86	3960	56	-71	60	84	75
I0E1	50	96	43	4200	62	-29	30	51	57
I0E10	50	68	-92	4120	69	-56	23	63	38
I0E11	50	98	4	5320	94	-62	67	39	72
I0E12	50	70	-53	8040	76	-20	48	66	46
I0E13	50	85	10	5640	92	-44	33	97	78
I0E14	50	72	-32	7960	86	-11	45	49	54
I0E15	50	78	16	6520	81	-68	62	96	98
I0E16	50	90	-11	5080	43	34	51	99	76
I0E17	50	71	70	3000	57	16	31	64	40
I0E18	50	82	-20	4040	54	55	10	92	91
I0E19	50	74	46	3880	39	10	38	46	51
I0E2	50	92	-26	5400	49	-38	25	90	68
I0E20	50	88	-56	6120	41	94	72	59	87
I0E21	50	86	64	6760	45	4	36	80	44
I0E22	50	99	-17	5880	51	91	21	43	70
I0E23	50	73	97	7400	59	37	68	69	49
I0E24	50	75	-47	3640	73	61	65	82	35
I0E25	50	83	25	4760	99	52	11	47	71
I0E26	50	89	-77	4520	86	7	34	93	42
I0E27	50	93	67	3320	88	82	52	55	81
I0E28	50	95	-38	7640	74	28	54	48	55
I0E29	50	80	85	7320	82	76	24	98	74
I0E3	50	76	76	3400	64	-83	63	62	48
I0E30	50	77	-71	6840	71	88	16	61	41
I0E31	50	91	31	6200	90	43	58	76	69
I0E32	50	67	1	5560	67	1	40	67	67
I0E33	50	53	88	7160	78	73	20	50	59
I0E34	50	38	-41	6920	72	31	50	83	77
I0E35	50	42	28	5720	85	40	55	44	66
I0E36	50	58	-74	7720	70	85	17	72	86
I0E37	50	40	7	4840	98	79	27	89	61
I0E38	50	65	-80	3560	68	67	61	57	95
I0E39	50	50	61	3240	97	49	66	78	52
I0E4	50	94	-5	6280	36	-77	53	45	73
I0E40	50	47	-50	4440	79	25	37	40	97
I0E41	50	55	91	6440	47	19	39	60	84
I0E42	50	37	-35	5960	50	97	71	81	45
I0E43	50	66	94	7000	65	58	57	71	96
I0E44	50	36	-2	5800	40	64	13	95	62
I0E45	50	64	55	3080	58	22	32	68	88
I0E46	50	49	-8	5480	42	46	47	37	56
I0E47	50	62	34	3160	38	13	35	85	80
I0E48	50	56	-14	4600	53	70	18	38	36
I0E49	50	44	13	6040	91	-32	29	35	58
I0E5	50	69	82	7560	66	-65	19	77	39
I0E50	50	63	-68	8120	77	-14	49	70	94
I0E51	50	52	22	7080	80	-53	70	42	43
I0E52	50	60	-44	7240	95	-8	42	88	83
I0E53	50	46	58	5000	93	-92	8	75	47
I0E54	50	48	-62	4360	89	-2	44	54	90
I0E55	50	35	19	5240	83	-89	59	91	64
I0E56	50	61	-95	3720	75	-35	12	65	85
I0E57	50	59	49	7480	61	-59	15	52	99
I0E58	50	51	-23	6360	35	-50	69	87	63
I0E59	50	45	79	6600	48	-5	46	41	92
I0E6	50	84	-59	7880	37	-47	14	56	82
I0E60	50	41	-65	7800	46	-80	28	79	53
I0E61	50	39	40	3480	60	-26	26	86	79
I0E62	50	54	-83	3800	52	-74	56	36	60
I0E63	50	57	73	4280	63	-86	64	73	93
I0E64	50	43	-29	4920	44	-41	22	58	65
I0E7	50	87	52	6680	55	-23	43	94	37
I0E8	50	79	-89	4680	87	-17	41	74	50
I0E9	50	97	37	5160	84	-95	9	53	89

SearchT_OC3_Stealth	SearchT_Mspeed	SearchT_OC3_OT3	SearchTnoNVG_SR	TC_ComRel	SearchT_ITR	SearchT_sskp	SearchT_NT	Blue Cas	Red Cas
79	860	-2	70	81	247	7600	1	1.1	3.72
45	700	49	54	94	345	4410	1	1	3.52
88	550	37	9	50	324	2320	0	0.7	3.56
49	590	61	28	59	240	2760	0	0.96	3.24
82	470	-41	69	96	65	1330	1	0.76	3.5
60	380	-95	41	69	114	3090	1	0.68	3.14
90	650	85	17	88	1	4080	0	1.1	3.52
63	990	13	37	87	163	1770	0	1.86	3.16
59	850	91	45	73	142	2980	1	2	3.52
80	880	58	31	82	51	1000	1	1.16	3.52
68	370	-17	42	86	219	1550	0	0.68	3.74
81	630	-62	60	91	23	3970	0	0.6	3.88
92	450	-8	34	72	359	7160	0	0.52	3.78
61	360	40	27	41	191	2210	1	1.34	3.82
98	660	76	19	57	415	3200	1	0.92	3.6
51	810	-71	44	56	254	2870	0	1.28	3.76
94	720	-53	72	39	317	2430	0	0.86	3.76
58	950	-65	14	45	121	5620	1	1.66	3.68
95	760	-26	32	64	16	7050	1	2.02	3.46
43	560	88	57	51	100	5180	0	1.68	3.26
72	430	31	55	58	170	7930	0	1.84	3.58
41	610	-80	22	90	394	4850	1	0.8	3.6
77	570	7	12	85	275	5730	1	1.72	3.38
56	520	-44	16	98	408	5400	0	0.7	3.7
50	840	52	67	97	366	4740	0	2.74	3.62
97	930	34	50	74	373	6390	0	1.86	3.34
67	670	1	40	67	226	4520	1	1.08	3.54
55	480	4	10	53	205	1440	0	1.66	3.66
89	640	-47	26	40	107	4630	0	0.6	3.68
42	890	10	46	62	93	1880	1	1.54	3.6
78	820	46	64	36	44	3640	1	1.4	3.8
48	830	-20	33	68	422	2100	0	4.08	2.92
96	900	-68	15	92	268	2540	0	1.14	3.64
64	420	16	62	71	296	1660	1	1.56	3.14
86	510	22	47	66	30	6940	1	0.58	3.66
87	540	94	56	79	443	3530	1	0.98	3.48
35	740	79	21	80	72	5290	0	0.88	3.66
39	400	25	29	99	149	7820	0	0.8	3.7
46	790	-35	71	84	128	6720	1	1.34	3.64
85	750	-59	52	75	212	6280	1	1.4	3.68
52	870	43	11	38	387	7710	0	1.5	3.4
74	960	97	39	65	338	5950	0	1.66	3.74
44	690	-83	63	46	450	4960	1	0.98	3.58
71	350	-11	43	47	289	7270	1	1.32	3.52
75	490	-89	35	61	310	6060	0	0.8	3.38
38	440	70	65	42	184	6500	1	1.54	3.56
54	460	-56	49	52	401	8040	0	0.92	3.54
66	970	19	38	48	233	7490	1	1.62	3.5
53	710	64	20	43	429	5070	1	1.9	3.02
73	980	-38	53	93	261	6830	0	2.78	2.72
36	680	-74	61	77	37	5840	0	1.1	3.42
83	530	73	36	78	198	6170	1	0.72	3.46
40	620	55	8	95	135	6610	1	1.12	3.54
76	390	67	66	89	331	3420	0	0.92	3.6
39	580	28	48	70	436	1990	0	0.7	3.78
91	780	-86	23	83	352	3860	1	0.8	3.6
70	920	-14	18	63	156	7380	0	1.12	3.52
62	910	-29	25	76	282	1110	1	0.92	3.36
93	730	82	58	44	58	4190	0	0.86	3.56
57	770	-5	68	49	177	3310	0	0.76	3.84
84	500	-50	13	37	86	4300	1	0.34	3.62
37	410	-32	30	60	79	2650	1	0.84	3.52
47	800	-92	24	55	9	5510	0	1.14	3.6
99	600	-77	59	54	380	3750	1	0.84	3.14
65	940	-23	51	35	303	1220	1	1.38	3.1

Table 3. Table of Design

APPENDIX C. REGRESSION TREE CODES

The results obtained from the regression trees are displayed below.

A. CODE FOR REGRESSION TREES OF BLUE CASUALTIES

```
*** Tree Model ***
Regression tree:
snip.tree(tree = tree(formula = Mean.Alleg1Cas.Blue.. ~ Ter.OC3.EasTer +
Ter.OC3.InjFr. + Ter.OC3.sskp. + Ter.OC3.Stealth. + Ter.OC3.OT3. +
Ter.OC3.SR. + Sniper1Stealth + Search.FWP.Stealth. +
SearchT.OC3.Stealth. + SearchT.MSpeed. + SearchT.OC3.OT3. +
SearchNoNVG.SR. + TC.ComRel. + SearchT.ITR. + SearchT.sskp. +
SearchT.NT, data = aydin.3data.By..Identifier., na.action = na.exclude,
        mincut = 5, minsize = 13, mindev = 0.01), nodes = 19.)
Variables actually used in tree construction:
[1] "SearchT.MSpeed."    "Ter.OC3.OT3."      "SearchT.OC3.Stealth."
[4] "TC.ComRel."         "Ter.OC3.Stealth."
Number of terminal nodes:  8
Residual mean deviance:  0.1572 = 8.958 / 57
Distribution of residuals:
      Min.    1st Qu.     Median      Mean      3rd Qu.     Max.
 -0.788900 -0.205000   0.004615   0.000000  0.145000   1.911000
```

B. CODE FOR TRUNCATED VERSION OF REGRESSION TREES OF BLUE CASUALTIES

```
*** Tree Model ***
Regression tree:
snip.tree(tree = tree(formula = Mean.Alleg1Cas.Blue.. ~ Ter.OC3.EasTer +
Ter.OC3.InjFr. + Ter.OC3.sskp. + Ter.OC3.Stealth. + Ter.OC3.OT3. +
 Ter.OC3.SR. + Sniper1Stealth + Search.FWP.Stealth. +
```

SearchT.OC3.Stealth. + SearchT.MSpeed. + SearchT.OC3.OT3. + SearchNoNVG.SR. + TC.ComRel. + SearchT.ITR. + SearchT.sskp. + SearchT.NT, data = aydin.3data.By..Identifier., na.action = na.exclude,
mincut = 5, minsize = 10, mindev = 0.01), nodes = c(5., 4.))

Variables actually used in tree construction:

[1] "SearchT.MSpeed." "Ter.OC3.OT3." "Ter.OC3.Stealth."

Number of terminal nodes: 4

Residual mean deviance: 0.1967 = 12 / 61

Distribution of residuals:

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
-0.78890	-0.20510	-0.06514	0.00000	0.17500	1.91100

C. CODE FOR REGRESSION TREES OF RED CASUALTIES

*** Tree Model ***

Regression tree:

snip.tree(tree = tree(formula = Mean..Sqd15Cas. ~ Ter.OC3.EasTer +
Ter.OC3.InjFriends + Ter.OC3.sskp + Ter.OC3.Stealth + Ter.OC3.OT3 + Ter.OC3.SR + Sniper1Stealth + teamNVG.FWP.Stealth + teamNVG.OC3.Stealth + teamNVG.D.MSpeed + teamNVG.OC3.OT3 + noNVG.OC3.SR + TC.ComRel + teamNVG.ITR + teamNVG.OC3.sskp + teamNVG.OCt3.NT, data = aydin.2.data.By..Identifier., na.action = na.exclude, mincut = 5, minsize = 10, mindev = 0.01), nodes = c(17., 5.))

Variables actually used in tree construction:

[1] "Ter.OC3.Stealth" "Ter.OC3.OT3" "teamNVG.D.MSpeed" "teamNVG.OCt3.NT"

[5] "teamNVG.ITR"

Number of terminal nodes: 8

Residual mean deviance: 0.01212 = 0.6906 / 57

Distribution of residuals:

Min. 1st Qu. Median Mean 3rd Qu. Max.

-0.288000 -0.057140 0.002857 0.000000 0.062860 0.232000

D. CODE FOR TRUNCATED VERSION OF REGRESSION TREES OF RED CASUALTIES

*** Tree Model ***

Regression tree:

snip.tree(tree = tree(formula = Mean..Sqd15Cas. ~ Ter.OC3.EasTer + Ter.OC3.InjFriends + Ter.OC3.sskp +Ter.OC3.Stealth + Ter.OC3.OT3 + Ter.OC3.SR + Sniper1Stealth + teamNVG.FWP.Stealth + teamNVG.OC3.Stealth + teamNVG.D.MSpeed + teamNVG.OC3.OT3 + noNVG.OC3.SR + TC.ComRel + teamNVG.ITR + teamNVG.OC3.sskp + teamNVG.OCt3.NT + Ter.OC3.sskp, data = aydin.2.data.By..Identifier., na.action = na.exclude, mincut = 5, minsize = 10, mindev = 0.01), nodes = c(2., 7.))

Variables actually used in tree construction:

[1] "Ter.OC3.Stealth" "teamNVG.ITR"

Number of terminal nodes: 3

Residual mean deviance: 0.02013 = 1.248 / 62

Distribution of residuals:

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
-0.4180	-0.1061	0.0020	0.0000	0.1020	0.2539

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APPENDIX D. BOOTSTRAP CODE FOR THE COMPARISON OF THE BASELINE SCENARIO AND THE RESERVE UNIT

Associate Professor Thomas W. Lucas developed the bootstrap code implemented in this study and the code is given below:

```
#  Define exchange ratio function
er <- function (x,y) {return(sum(x)/sum(y))}
#  Do for conscripts
r.con <- combo.df$red.con
b.con <- combo.df$blue.con
sum(r.con)
sum(b.con)
sum(b.con)/sum(r.con)
#  Do for reserves
r.res <- combo.df$red.res
b.res <- combo.df$blue.res
sum(r.res)
sum(b.res)
sum(b.res)/sum(r.res)
#  Build bootstrap
index <- seq(1, 200, 1)
B <- 1000
out.con <- rep(0,B)
out.res <- rep(0,B)
for (i in 1:B)
   {
    tempi1 <- sample(index, replace = T)
    tempi2 <- sample(index, replace = T)
    out.con[i] <- er(b.con[tempi1], r.con[tempi1])
    out.res[i] <- er(b.res[tempi2], r.res[tempi2])
   }
hist(out.con)
hist(out.res)
#  See how often out.res is less than out.con
total <- 0
for (i in 1:B)
   {
     total <- total + sum(  out.res < out.con[i] )
   }
pval <- total/(B^2)
pval
```

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